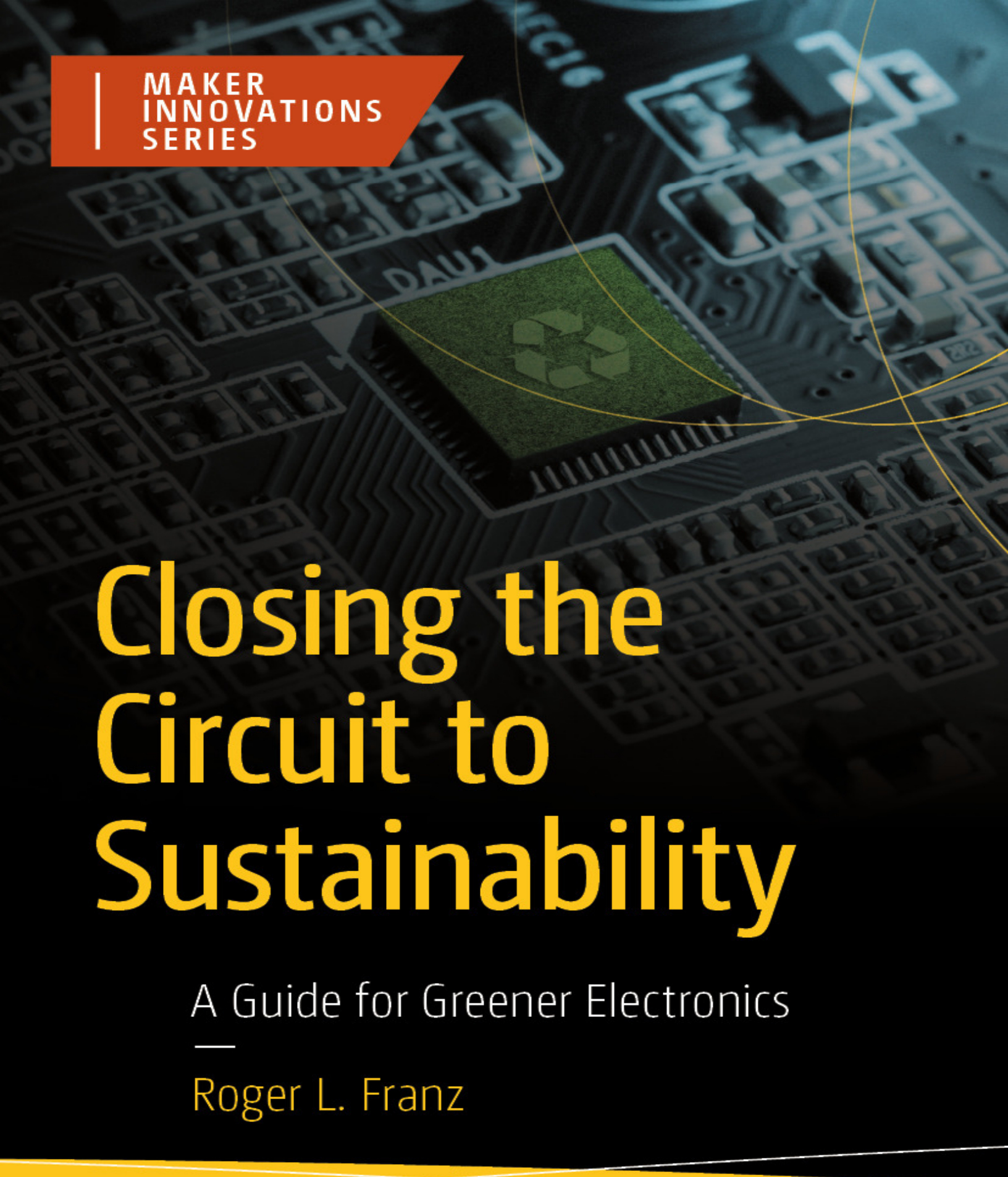


Closing the Circuit to Sustainability

A Guide for Greener Electronics

Roger L. Franz

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This work is dedicated to my dear wife, Nancy, and my older brother, Eldon.

Nancy has been by my side for most of my working life. We raised three children and are now enjoying our four grandchildren. While I spent some years working away, it is good to be back home and close to them all. Nancy deserves my special thanks for putting up with my long hours of research and writing.

Eldon, Professor Emeritus of ecology, first introduced me to the concept of ecology when I was a chemistry student in college, and before that, to my first transistor radio. My love of both chemistry and electronics has remained vital to me throughout my career in my many roles in the electronics industry and before that in the medical laboratory.

This book is for the next generation of electronics and those who continue to benefit from this remarkable technology.

Introduction

One does not have to look far to find electronics in daily life. From TVs to personal computers to cell phones, such devices are all around us. Electronics technology permeates everything else too, from transportation, to medicine, to business, education, entertainment, and even preparing food. New devices appear on the scene and become obsolete almost faster than we realize; this has become a problem of its own.

The demands of an increasing population that strain the resources of our limited Earth become more apparent every day. These demands extend well beyond the realm of electronic circuits to nearly every flow of material and energy set forth by human activity. It is the potential to improve the environmental footprint of electronics specifically that gave rise to the need for a book like this.

Now you might ask, why this particular book when there are so many other volumes on technology, nature, green citizenship and so on? The author, who has worked on bits and pieces of this puzzle for decades, felt the need to put a coherent and compelling story in one place. In fact, the contents of many of the chapters have appeared as their own short stories in different industry journals and conferences. Here they are all together in one accessible volume. While the book is not about electrical circuits, some familiarity with the components that make up electronics products would be useful. Nor is this a textbook of green chemistry, although again some feel for chemical elements and compounds and how they are used in modern products will come in handy. Most importantly, a passion like that of the author, who has always been eager to know how things work and how Earth can be a better place, should be right at home here.

After some initial perspectives presented in Chapter 1, Chapter 2 introduces how we have come to know what is in electronic products—besides electrons, of course—through the use of material declarations by industry. These documents have provided an understanding of how

the basic raw materials, including minerals, petroleum products, and so forth, enter the electronics supply chain in the first place. It is thanks to several key regulations on hazardous substances around the world that first brought focus to such reporting. The knowledge so accumulated can now be used for paying attention to the good stuff as well as the bad, as covered in Chapter 3. Given this basis of data, Chapter 4 moves to how the materials in electronics could be made more environmentally friendly and sustainable. Already the theme that *business as usual will not be good enough* becomes evident.

As for the difficult closed loop of returning highly refined and technically fussy electronic goods back to the Earth—as happens naturally, for example, with a forest decaying and growing new trees; this is quite unnatural for electronics. So, as explained in Chapter 5, we do the best we can to recycle current designs and materials that were honestly never intended to become a closed loop in the first place.

Along the way, quite a body of technical standards and similar documents have been developed by knowledgeable subject matter experts to provide guidance that tends to be overlooked, thus deserving Chapter 6 of its own.

Almost without exception, electronics runs on electrical energy, which brings us to Chapter 7. Electricity can be electromagnetically generated from mechanical motion like air or water or steam, or more directly by photons of sunlight striking a sensitive cell. Other means, of course, like nuclear energy, are possible too but will not be debated at length here. Growing concerns over large data farms and their huge demand for electricity will be briefly considered, as will growing demands on diverse minerals to make batteries.

Electronic social media has earned its own chapter since a group of like-minded individuals with passion about their topic can often do more than a lone scholar. Especially given current trends for many types of writing to be published informally as blogs, Chapter 8 provides links to like-minded groups to enable the reader's outreach in this direction. Enjoy the benefit of their company, armed with ideas from this book.

Fully realizing that we do not expect this small volume to contain anywhere near all the answers or be able to predict what the inevitable march of electronics technology may be able to deliver in the future, a companion piece by the author called "A Pocket Dictionary of Future Electronics" (www.slideshare.net/slideshow/a-pocket-dictionary-oftomorrows-electronicsfranzipctlp2021pdf/252008752) lists 50 upcoming directions for this dynamic industry. Some of them follow the prior trend of introducing new and novel materials with little consideration for environmental sustainability. Others, such as artificial intelligence, internet everywhere, and massive data centers, can only be sustainable if the hardware that enables them becomes more sustainable. The prospects of carbon nanotechnology show the most promise at this early stage of its development. At this time it is not clear how these new materials technologies might—or might not—contribute to more sustainable electronics of the future.

Finally, Chapter 9 steps back to offer some broader perspectives for trends that have already occurred, or we see occurring already. One of these centers around the movement away from old-school heavy and toxic metals and complicated arrangements of many of the known chemical elements and their compounds, to a more arguably sustainable set of materials based more simply on the familiar element of life itself, carbon. A unique arrangement of nanocarbon may even solve the basic contradiction of conductors needing to be metals and insulators having to be totally different materials like polymers. The prospect of finally resolving this duality even rings with ancient religious and philosophical tones.

Since even life itself is made with multiple elements and molecular building blocks, we also have no unrealistic expectation that electronics technology could ever be as simple as a lump of coal. But the signs are that electronic materials can be fundamentally simpler and more sustainable given enough innovation and will to do so. Whether we as humanity will take up the challenge will be up to the economics and history books to tell.

Two Definitions of Environmental Sustainability

1. "Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits – not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities."

   (United Nations Report of the World Commission on Environment and Development, "Our Common Future." Part 3. Sustainable Development, section 27. Gro Harlem Brundtland, Chair, Aug. 4, 1987.)

2. "Environmental sustainability: Ability to maintain an ecological balance of the natural environment and to conserve natural resources to support the wellbeing of current and future generations. Note to entry: Wellbeing includes related economic and social aspects."

   (International Electrotechnical Commission, *IEC 62542 ED2*, Environmental standardization for electrical and electronic products and systems – Glossary of terms, Mar 15, 2024.)

Author's Note

International and regional regulations are a key topic in this book. Since regulations are in almost constant change, what is written here may not precisely reflect the latest legal developments. Guidance is provided here in good faith but shall not be construed as professional advice about any particular situation with respect to compliance with current legal statutes or requirements.

Any source code or other supplementary material referenced by the author in this book is available to readers on GitHub. For more detailed information, please visit https://www.apress.com/gp/services/source-code.

Acknowledgments

Given the interdisciplinary nature of this book, there are too many individuals to name here. Rather, the author gratefully acknowledges the collected efforts of the following groups:

- Chemical organizations like The American Chemical Society and Chemical Abstracts Service
- Electronics organizations like IEEE and standards organizations like IPC, IEC, and ISO (these will all be spelled out in the book)
- Industry journals in the converging worlds of electronics, supply chain, and recycling
- Universities and academic programs specializing in ecology and sustainability
- National and local organizations that fight for a better environment and more sustainable communities
- Indigenous peoples who teach the importance of respecting life on this Earth
- Responsible governments at the international (UN), national (EU and other countries) state, and local levels who help define legal limits
- Employers who recognize the value of sustainable business practices and corporate responsibility
- Social media groups, friends, and neighbors.

To these, and those I have failed to mention, I express my sincere thanks.

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Clean Planet for All

International Society for Industrial Ecology (ISIE)

Recyclers

e-Stewards Certified Recyclers

e-waste management

The Recycled Materials Association (ReMA)

Bureau of International Recycling (BIR)

The Recycle Global Exchange (RGX)

RIOS: The Recycling Industry Operating Standard

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1. Perspectives: Electronic Materials—Conductors, Insulators, and Everything Else

Roger L. Franz[1] ✉
(1) Mundelein, IL, USA

This book is about electronics. Even the simplest of electrical circuits is a study of opposites. On one hand, materials that conduct electricity are an absolute must. To keep everything from simply shorting out and operating safely, insulators are also an absolute must. In between the two extremes lie even more exciting details in complex circuitry.

What you will take away from this chapter

- Know how the history of electronics has brought us to the present
- Recognize some successes and best practices so far
- Imagine how this momentum will take electronics forward
- Discover a vision of the future

Without any theory, we will jump right in with some practical talk about circuit elements or components. As a colleague of mine once said, “Parts is parts.” Meaning, of course, components. Briefly, these are as follows:

- Active devices that typically operate between the extremes of conductors and insulators are *semiconductors,* including *transistors, diodes,* and *integrated circuits* of all types.

- Passive components like *resistors* purposely do not conduct perfectly, allowing for control of voltages in the circuit, among other things.
- Other components that are usually considered to be passive are used to intelligently control the behavior of alternating current circuits (*capacitors* and *inductors)*.
- Parts that help connect all the elements together include *printed circuit boards*, made of the two opposites, conductors and insulators, with conductors where they are needed, and the rest of the landscape offering high insulating resistance. *Connectors* are similar in that they too must provide high conductivity where needed and behave as an insulator everywhere else. Even a simple hookup wire or line cord that connects household goods to power must conduct electricity as needed, yet behave just the opposite way on the outside as an insulator for safety.

Many of the basic principles are known, although the push for new electronics technology has largely left them behind. For example, Barry Commoner listed the following four basic laws of ecology in his book *The Closing Circle: Nature, Man and Technology* (Alfred A. Knopf, 1971):

1. Everything is connected to everything else.
2. Everything must go somewhere.
3. Nature knows best.
4. There is no such thing as a free lunch.

Not much later, 12 principles of green chemistry and 12 principles of green engineering were proposed by the American Chemical Society (ACS) (see www.acs.org/green-chemistry-sustainability/principles/12-principles-of-green-chemistry.html). More will be said about these principles in later chapters of this book.

The principles need to be taken seriously and become a priority for electronics to develop, but these steps have lagged behind. Changing how an entire industry and its supply chains operate in a give economic and political environmenent is not easy. Support from industry standards may be of additional help, but recognition and adoption are needed for the standards to be of value.

It is for these reasons and many more that the journey to complete sustainable electronics is not easy. This book discusses materials whose use should be limited, due to either being unhealthy, or in short supply, or both. Subsequent chapters explain in more detail where electronic materials come from, and where they should ideally go when they have lived a useful life in an electronic product. This book offers some visions of electronic materials that are badly needed for the next generation of sustainable electronics.

Vectors

A vector is defined as a quantity having both direction and magnitude. Electronics has both, but needs a change in direction to become more sustainable.

A bit of history may help frame the growing need for more sustainable electronics. Just a little more than 50 years ago, electronics meant telegraph, telephones, and radio. TVs and computers ran on vacuum tubes and may have been housed in cabinets made of wood. They were heavy. Cars had only limited electrical content compared to today's vehicles and did not have circuit boards or computers. Only recently were significant efforts made to recognize and improve the environmental footprint of the rapid growth of so many products globally.

However, miniaturization of solid-state circuits and circuit boards has only continued to increase the complexity of electronics and diversity of the opposites of conductors, semiconductors, and insulators. What may not be so apparent is what materials are needed for all the different component types.

While electronics in the age of microelectronics developed rapidly and did benefit from reduced weight and miniaturization, its complexity continued to increase without much fundamental thought about how to reverse the whole product life cycle using so many different materials. We explore the life of electronics materials in some detail in subsequent chapters.

Since the invention of the transistor in 1947, solid-state electronics grew explosively, and so did their quantity and distribution around the world. Today, familiar devices like TVs, computers, and mobile phones now number well into the billions. In fact, these devices greatly outnumber the world's human population. Computers, software, and wireless are literally everywhere.

Since the first four industrial revolutions (from mechanization and steam power to mass production and electrification to computers and automation to cyber-physical systems), electronics technology continues to rapidly move forward with unparalleled magnitude. This evolution of revolutions has been documented by the US National Institute of Standards and Technology (NIST). (See P. Toth, "Cybersecurity and Industry 4.0—What You Need to Know," May 11, 2022. Available at www.nist.gov/image/industry-40-phases.)

We are now entering Industry 5.0, which is bringing new capabilities and challenges such as the following ones listed by H. Kyriakakis in the October 29, 2024 *Forbes* article "What Does Industry 5.0 Mean Today?" (see www.forbes.com/councils/forbestechcouncil/2024/10/29/what-does-industry-50-mean-today/):

- Robotics
- Biomimicry
- Nanotechnology
- Renewable energy
- Industrial ecology
- Green chemistry

- Sustainability

The last few points in bold are playing significant roles in shaping the future.

Why is this important now? A little more history clearly tells us why. We now realize that mass industrial production as a wasteful, one-way material flow must change. Pollution is a prime example. The Polluter Pays principle, while based on common sense, and one might say simply good corporate citizenship, was not easy at first, and is still being fought by special interests. Pollution prevention became a new regulatory requirement for many industries and began to be realized through the use of Best Available Technology for specific operations.

In 1969, industrial waste in the Cuyahoga River in Cleveland, Ohio, caught fire. This became an eye-opening event that helped people recognize what was being done to the natural environment.

More specifically for consumer electronics, the environmental impact was amplified by the rapid deployment of new technology, making old devices quickly obsolete. While good for commerce, the volume of end-of-life equipment was a new problem. Some of the substances in this waste were toxic. Regulations to address these problems entered into force in the European Union (EU) and other regions around the world, including several US states.

A new acronym was created, put into force by a European Commission Directive of the same name: WEEE = Waste Electrical and Electronic Equipment. The need for regulations and improvement of electronic waste processing continues to be a challenge and calls for new approaches to design and material selection.

While this is not intended to be a complete history of environmental issues, the following is a reminder of a few major milestones in this journey into the realm of our current topic: electronics.

1962: *Silent Spring* published by Rachel Carson
1967: First issue of the journal, *Environmental Science and Technology*

1987: United Nations Brundtland Commission report, “Our Common Future,” which defined *sustainability*
1993: First IEEE International Symposium on Electronics and the Environment
1996: First issue of *International Journal of Life Cycle Assessment*
1997: First issue of *Journal of Industrial Ecology*

Soon, public action and government regulations entered the picture.

1970: First “Earth Day” (public event)
1970: US Environmental Protection Agency (EPA) formed
1976: US Toxic Substances Control Act (TSCA)
2003: EU WEEE Directive enters into force (Waste Electrical and Electronic Equipment)
2004: EU RoHS Directive enters into force (Restriction of Hazardous Substances in electronics)
2007: EU REACH Directive (Registration, Evaluation, Authorisation and Restriction of CHemicals), which applies to all articles placed in the EU market, and continues to be updated with new substances of very high concern (SVHCs)

This is only a partial list. The number of regulations impacting the electronics industry and supply chains is huge, international in nature, and growing. These developments are just a small part of the overall topic of sustainability introduced on the first page of this book.

By the end of this book, you will see that current materials and product designs that were never designed for sustainability in the first place can be replaced by new generations of electronics that can be built and recovered differently.

But first steps first. Let’s begin with a significant early accomplishment.

A Short Success Story

In 2006, the EU RoHS Directive created a kind of “lead-free revolution” for many international companies, including those making high-volume

consumer products. *One main benefit was a thousandfold reduction of lead—a known neurotoxin—in solder.* While the story is kept brief here, a significant amount of research and development was needed to make it happen. These efforts must continue to other areas, as will be detailed in later chapters.

The new "lead-free" solder alloy generally adopted by industry had a higher melting temperature, requiring new equipment and processes. Components that would be soldered needed to be rated for the higher temperatures, resulting in new handling, testing, and mitigation for moisture-sensitive components not to explode or "popcorn" during assembly. In retrospect, this was quite an achievement to reduce the lead content of electronic goods by a thousandfold. The exact calculation is as follows:

- Tin-Lead eutectic solder: 37% lead
- Tin-Silver-Copper solder: typically, less than 0.03% lead, a typical residual amount from processing most metals
- 37/0.03 = 1,233, or roughly a thousandfold reduction

This example shows that with enough motivation and cooperation, materials used in electronics can be improved

However, while reducing the content of toxic metal is a notable accomplishment, like most changes, some downsides may also be expected. The reflow ovens used to manufacture high-volume circuit boards needed to run at higher temperatures with lead-free solder, using more electricity. Less lead meant more silver and copper, which have their own resources and supply chain complexities. Some components were not compatible with the new soldering temperatures. High-reliability products had to retain tin-lead for reliability purposes under conditions like mechanical shock and vibration, and applications in space electronics where tin whiskers could unexpectedly grow and cause short circuits. Finally, reducing lead in solder is a small part of the overall market for lead that remains in other applications like shielding and storage batteries. But this remains a notable example of what can be done.

We explore similar trade-offs in Chapter 6 of this book.
After the product is manufactured and used, what happens next?

Chasing Arrows

The recycling logo consisting of three chasing arrows should look familiar, along with the instructions to Reduce, Reuse, and Recycle. But how can that be achieved with such a diverse commodity as electronics? We leave most of that discussion to later chapters. For now, it is useful to know that—luckily—the general design trend toward smaller and lighter-weight products has helped to reduce some aspects of resource use. At the same time, however, the increasingly rapid obsolescence of older products in favor of new ones has acted in the opposite direction. In some cases, product life extensions can be achieved by software updates, but even this may be limited in practice when the latest software will not even run on the old hardware.

Unlike a glass bottle, an aluminum can, or paper products, electronic goods are extraordinarily complex. It should come as no surprise that precious metals like gold and silver lead the way economically, along with the commonly used conductor, copper, along with other valuable metals, while the other fractions have less economic value and are not so easily separated and recycled like metals.

While commercially viable processes for recycling copper and precious metals were quite an achievement by the industry some 20 years ago, it remains far from perfect. More details and improvements are still needed and will be discussed in Chapter 5.

This is a summary of the good and bad today:

- **Copper and precious metals**: Gold and silver can be economically recovered. Lead and other metals may be included in this fraction.
- **Circuit boards**: Thermoset resin, glass fibers, and organic coatings are difficult to recover and of low economic value. Historically, copper as the circuit conductor can be handled in the copper recycling stream.

- **Solder**: Metals like tin, silver, and copper are also partially handled in the copper recycling stream.
- **Wires**: Copper and plastic insulators require separation but then can be handled by the copper recycling stream.
- **Mechanical parts**: Ferrous metals can be separated magnetically and, if present without contaminants (difficult at best), can merge with one of the largest recycling streams for iron and steel alloys.

  Nonferrous metals like aluminum can be separated by eddy current; once again, if separable without contaminants, they can merge with another commercially successful recycling stream.

Plastics: Some thermoplastics can be recycled, but few engineering types have a market at present.

The following are exceedingly difficult to efficiently recycle:

- **ICs (Integrated Cirtcuitys)**: Thermoset resin is a common device package, housing metal conductors to bring the complex thin films of the active semiconductor die (chip) to connect to the outside circuit.
- **Ceramic components**: They contain other materials, but ceramics have no mainstream recovery flow.
- **Electrolytic capacitors**: They contain liquid electrolytes.
- **Tantalum capacitors**: Tantalum oxides present unique problems.
- **Displays**: Metal and metal oxides present unique problems, for example, the transparent conductor, indium tin oxide.

At this juncture, let us ask how we measure what we want to achieve with electronic hardware sustainability, and better yet, calculate how we are doing? The recognized method is not just for electronics, but for all kinds of products and activities, and is called the Life Cycle Assessment (LCA). Products begin with raw materials selected for the given design, and once manufactured, are distributed to the market where they enter the use phase. Eventually, the product will reach the end of its useful life, unless extended by reuse for some other purpose or life is extended by repair or refurbishment; the eventual disposal phase will occur, and whatever cannot be recovered or recycled will require disposal. What has been lacking is attention to the

increasingly complex demands on raw materials, and over-reliance on the disposal and waste steps. Even consideration for the use phase, which for electronics almost always means the use of electrical power, has needed attention.

Sustainability depends on optimizing and reducing environmental impacts at every stage.

More than a dozen impact metrics can be calculated using the LCA method. For now, we can summarize the main ones in just a few categories:

- Material usage and resource depletion
- Emissions to air, water, or solid waste
- Toxicity to life, including humans
- Energy usage, which in turn may deplete nonrenewable materials and result in emissions like carbon dioxide and various pollutants

A simplified sustainable product life cycle is shown in Figure 1-1.

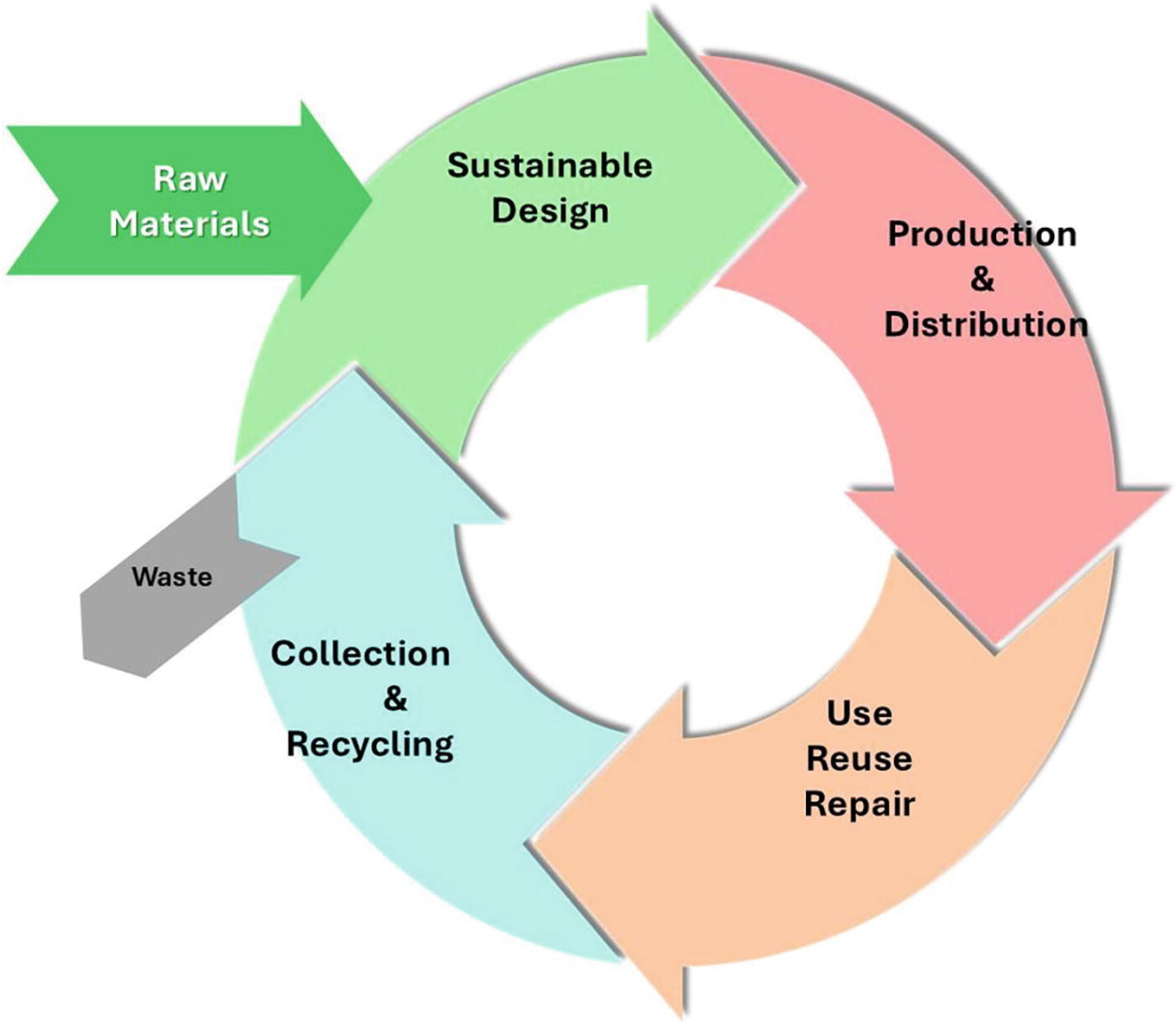


Figure 1-1 Circular product life cycle

A typical electronics product life cycle begins with raw materials that are selected using sustainable design principles and tools. Next are the production and distribution phases of the finished product. The traditional use phase includes provisions to extend product life through reuse and repair. Finally, the last phase collects the end-of-life goods and recycles and recovers as many materials as possible, sending them back to enable fewer raw materials to be needed in the next cycle. What minor fractions are left as waste are then responsibly treated, which may include options for energy recovery. How to put plans into practical actions is covered in Chapter 4 and Chapter 5.

The Electronics Supply Chain Is Complex

Everything starts with raw material, whether metal ore, a petrochemical product, or natural sources like trees. These need to be made into all the different types of components needed for a given circuit, which then need to be assembled, typically using solder, as has been mentioned. The next few chapters discuss in detail the ways in which reporting and managing the many different materials in electronic products are being realized, first being how we even know what on Earth is in them.

Recall there are 92 naturally occurring chemical elements. Electronics have evolved to the point where some two-thirds of them are used to make today's electronics. As published by the US Geological Survey (www.usgs.gov/media/images/computer-chip-comparison), the number of chemical elements has grown every decade. There were 12 in 1980, 16 in the 1990s, and 60 after 2000. The trend continues to this day. One of the themes of this book is that continued use of resources without limit is not sustainable.

Several of the elements are in short supply globally, not to mention having geographical and political restrictions on their availability. These are called *rare earth elements*, *rare earth minerals*, or simply *rare earths*.

While the name is a bit of a misnomer, the rare earths are moderately abundant elements. But they are critical to energy and electronics and need development for better recovery and recycling processes. They are lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), plus scandium (Sc) and yttrium (Y). Their applications are discussed in Chapter 7.

Not even listed here are elements critical for battery storage like lithium (Li) and cobalt (Co), display screens like indium (In, used in indium tin oxide, which is conductive but optically transparent), and

gallium (Ga) used in specialty semiconductors. The list goes on, the point being that the chemical complexity of electronics today has become large indeed.

Energy critical materials have now been added to the list of chemical elements used in electronics and electricity supplies. Thirteen of these are called rare earths (listed here using the standard chemical abbreviations): Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Yb, and Lu. Another six are in the platinum group, including Ru, Rh, Pd, Os, Ir, and Pt. There are five others now considered to be photovoltaic critical: Ga, Ge, Se, In, and Te. Yet "other" energy critical elements include substances like He, Li, Co, Ag, and Re. Some of these overlap with the computer chip list, but the message is that the periodic table of elements is becoming more and more consumed by electronics. Also note that carbon itself is not on this list, although some forms like graphite are; but more importantly, this abundant element of life itself is emerging as a strong candidate for next-generation sustainable electronic materials based on carbon nanotechnology.

The materials needed for electric vehicles are also creating demand for limited resources. In their favor, once put into service, rather than burning chemical fuel, the vision is for renewable electricity to power them. To the preceding list, let us add a few more: Niobium (Nb), Tungsten (W), Antimony (Sb), Magnesium (Mg), Manganese (Mn), and the minerals Graphite and Fluorspar.

Next on the Horizon

This introductory chapter concludes with an introduction to how future electronics may use circular materials that were never even considered in its early days.

Beyond Moore's law is a phrase that describes limits to silicon chips, and new electronic material sets are on the horizon. The following are some upcoming device technologies that will bring changes from today's materials set:

- Nanotechnology, including carbon nanotubes (CNTs) and graphene (see Chapter 4)
- Quantum computing
- Molecular electronics
- Spintronics
- MRAM (Magnetic Random Access Memory)
- Memristance (See the author's review of memristance and memristors: "Passive Components Get Active," *Electronic Design,* December 5, 2016, www.electronicdesign.com/technologies/components/passives/article/21802074/passive-components-get-active.)
- Additive manufacturing
- Printed electronics

The way that materials and parts are selected will also change. Look for the following:

- New materials and components developed without toxic substances
- Innovative design approaches based on abundant and renewable materials
- New substances fully evaluated with full LCA and toxicological studies *before* high-volume shipment
- Application of principles of green chemistry (see www.acs.org/content/acs/en/greenchemistry/principles/12-principles-of-green-chemistry.html) and green engineering (see www.acs.org/green-chemistry-sustainability/principles/12-design-principles-of-green-engineering.html)

The 12 principles of green chemistry are

1. Prevent Waste
2. Atom Economy

3. Less Hazardous Synthesis
4. Design Benign Chemicals
5. Benign Solvents and Auxiliaries
6. Design for Energy Efficiency
7. Use of Renewable Feedstocks
8. Reduce Derivatives
9. Catalysis (vs. Stoichiometric)
10. Design for Degradation
11. Real-Time Analysis for Pollution Prevention
12. Inherently Benign Chemistry for Accident Prevention

While detailing each of these principles is outside the scope of this book, it should be clear how they support the same end goals as sustainable electronics from the ground up.

Similarly, the following are the principles of green engineering:

1. Inherent Rather Than Circumstantial: Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.
2. Design for Separation: Separation and purification operations should be designed to minimize energy consumption and materials use.
3. Maximize Efficiency: Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

4. Output-Pulled Versus Input-Pushed: Products, processes, and systems should be “output pulled” rather than “input pushed” through the use of energy and materials.
5. Conserve Complexity: Embedded entropy and complexity must be viewed as an investment when making design choices on recycling, reuse, or beneficial disposition.
6. Durability Rather Than Immortality: Targeted durability, not immortality, should be a design goal.
7. Meet Need, Minimize Excess: Design for unnecessary capacity or capability (e.g., “one size fits all”) solutions should be considered a design flaw.
8. Minimize Material Diversity: Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
9. Integrate Material and Energy Flows: Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
10. Design for Commercial “Afterlife”: Products, processes, and systems should be designed for performance in a commercial “afterlife.”
11. Renewable Rather than Depleting: Material and energy inputs should be renewable rather than depleting.

While these theoretical goals are in line with the themes of this book, the author does not wish the reader to get too lost in theory. The public posting of these principles by the American Chemical Society (see file:///C:/Users/lbn6030/01_Chapter Submission/acs.org) is gratefully acknowledged, and recognition of these two dozen principles by the electronics industry is one of the purposes of this book.

While quite insightful for the time, those principles did not mention electronics. If that is your interest, you are in the right place.

Recognition of the green chemistry and engineering principles and putting into practice will help take us from Industry 5.0 to Industry 6.0 and beyond. It is all about vision, innovation, and the will to change. Electronics is well suited for change because it has powered change since its beginning.

Building on the vectors that brought us this far, we can complete the circuit to power a new era of s*ustainable electronics.*

Key Takeaways

This chapter introduced the fundamental duality of electronics—needing to both conduct electricity and not conduct electricity, and everything in between in the world of circuits. It also covered the modern problem of pollution and the first attempts at recycling electronic products that led to the introduction of the LCA and the concept of circularity. Several sets of principles were listed that will be applied in later chapters. The next chapter covers how we came to know about the material complexities of electronic products in the first place.

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2. Material Declarations

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Question: How do we know "What's In This Stuff" (WITS)?

Answer: Material Declarations

Personal note: The author somewhat jokingly used the WITS phrase for years while working in industry, including making some of the first requests for supplier material declarations and conducting chemical analyses on complete products like mobile phones. (These were unforgivingly ground up to powder and extracted with strong acids before being submitted to a chemical laboratory) It turns out that there is a book of this same name by Patricia Thomas: *What's In This Stuff?: The Hidden Toxins in Everyday Products—and What You Can Do About Them* (Perigee Trade, 2008).

While that book was revealing, the contents of electronic goods were not covered there. Read on to enter the material world of electronic materials.

What you will take away from this chapter

- How we know what we know about WITS for electronics
- Introduction to industry standards and reporting software
- Why the initial focus has been on regulated substances and substances of very high concern
- How material declarations can help move beyond regulated substances to support sustainability

We already know about chemical elements, different materials, and so on, but how did we gain the knowledge to even know "What's in this stuff?" This is more complicated than labeling a box of cereal because of the extensive supply chains in electronics. Another complication is that electronics manufacturers focus on electronics, not chemistry. Nonetheless, some specialization and cooperation, spurred on by never-ending regulations as explained next, has resulted in some very good data about what is, in fact, in the box. Here we break it down with practical examples since knowing about these substances is a prerequisite for making products more sustainable. We begin broadly with a list of substances that need to be carefully used and distributed not only in electronics but in all kinds of goods.

Substances of Very High Concern (SVHC)

This phrase has been quite precisely defined by the European Chemicals Agency (ECHA). The list of such substances is continually increasing, with new SVHCs being added to the list about twice each year ever since the first list was put into European Union (EU) law under REACH (Registration, Evaluation, Authorisation and Restriction of CHemicals) in the year 2008. It currently numbers some 250 substances, including not only those used in electronics but also all kinds of articles available in the marketplace.

There are several reasons for a substance to be placed on the SVHC list, which can be one or more of the following properties:

- Carcinogenic
- Mutagenic
- Toxic for Reproduction
- Persistent, Bioaccumulative, and Toxic
- Very Persistent and Bioaccumulative
- Respiratory Sensitizer

The EU's REACH, a Regulation of the European Commission, requires manufacturers of articles containing substances of very high

concern (SVHCs)—not limited to electronics—to communicate information to customers about the REACH Candidate List published by the European Chemicals Agency (ECHA). Since the list grows continuously, with updates approximately twice a year, to keep current, we suggest that the reader consult the latest list (see www.echa.europa.eu/candidate-list-table).

Unlike the Restriction of Hazardous Substances (RoHS) Directive, which essentially bans shipment of products in the EU if certain substance thresholds are exceeded (except for specific exemptions), any product containing REACH SVHC may still enter the market—however, up-to-date reporting obligations must be met.

The latest implementation of the EU's Waste Framework Directive (WFD) requires companies to report directly to an ECHA database, called Substances of Concern in Products (SCIP) (see https://echa.europa.eu/scip-database). While manufacturers need to ask their suppliers and report to their customers the status of REACH—whether the product contains SVHC or not—only those items containing SVHC in concentrations greater than 0.1% must be reported to the SCIP database. In this article, we discuss the database's background and driving force for SCIP reporting, and we show how it can be accomplished.

- If you are a manufacturer doing business in the EU, this will be important to your operations.
- If you are mainly just curious or concerned, the behind-the-scenes details that follow may not be of great interest to you, but you should know that the SCIP database is publicly available at www.echa.europa.eu/scip-database.

Be aware that it is a very large database- which itself is a testament to the need for understanding and action to better manage such substances all around us. WITS has opened many eyes to what is in not only electronics but countless other household and commercial articles.

EU Waste Framework Directive and Circular Economy

The goals of the WFD are noble and broad: to create a more circular economy where resources are recycled and recovered rather than discarded, hazardous substances are minimized, and more transparency is provided to end customers and waste operators fulfilling recovery roles. The following are the main objectives (see https://echa.europa.eu/understanding-wfd).

1. Decrease the generation of waste containing hazardous substances by supporting the substitution of substances of concern in articles placed on the EU market.
2. Make information available to further improve waste treatment operations.
3. Allow authorities to monitor the use of substances of concern in articles and initiate appropriate actions over the whole lifecycle of articles, including at their waste stage.

More generally, the EU is also moving forward with prioritizing and implementing its Green Deal (see https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en) to fight climate change and develop a sustainable economy. These efforts stand in sharp contrast to other regions like the United States, where Green New Deal legislation has stalled, and the topic of climate change remains divisive. Meanwhile, if you want to do business in the European Union, or your worldwide market requires attention to be competitive, read on.

SCIP Reporting Requirements

If your company does business in the EU, most likely you have already been collecting data on which items contain REACH SVHCs. Actually, the regulation applies to all articles, defined as "an object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition."

In other words, unshaped raw materials, liquids, and so on, aren't themselves articles. However, in most cases, electronic products are either simple articles or assemblies of articles called *complex objects*. And if the article is made with a mixture or solution, for example, an adhesive, that itself contains the SVHC, then the resulting article where adhesive is applied contains the SVHC, too.

For companies already meeting the existing REACH obligation, the basic information you're already tracking includes

- The article: the number, SKU, and so on
- The SVHC substance itself: description, CAS or EC number, and possibly the percent concentration
- Safe use information that must be shared with the public

SCIP introduces several new mandatory reporting requirements.

Primary Article Identifier Type: While it's mandatory that you choose a specific identifier for each article, your company likely already has this information. Choices include global trade item number, universal product code, catalog number, item number, and part number, as well as Other.
Production in the European Union: While an answer is mandatory, Unwilling to Disclose is a valid choice.
Article Category: This is defined under a system of Combined Nomenclature (CN code) (see https://ec.europa.eu/taxation_customs/business/calculation-customs-duties/what-is-common-customs-tariff/combined-nomenclature_en), as found in the TARIC system (see https://taxation-customs.ec.europa.eu/customs/common-customs-tariff-cct/tariff-classification-goods/eu-customs-tariff-taric_en and https://trade.ec.europa.eu/tradehelp/). This new attribute may come as a surprise unless you're already assigning harmonized tariff codes. While there are some 20,000 valid codes,

those for commodities like live animals and works of art will not be applicable for electrical goods.

Material Category: This is a new, unique, and very specific list of material types where the SVHC is located. Because your products may likely contain substances with RoHS exemptions, for example, lead or cadmium, here we list some of the material categories you will likely encounter and need to report. Of course, there may be others not listed here, as the latest January 2020 SVHC list includes 205 substances in all. There's a general category called Other that we understand may be reported initially, until this new kind of data becomes available.

- glass > borosilicate glass (common example, lead borosilicate)
- metal > brass (machinable brass containing lead)
- metal > cadmium and alloys (silver cadmium oxide contacts)
- metal > lead > lead alloy (high-temperature solder)
- ceramic > oxide ceramic > lead zirconium titanate (PZT) ceramic
- metal > aluminum alloys (machinable aluminum containing lead)
- metal > steel > alloy steel except stainless steel (machinable steel)
- plastic and polymers > polyvinyl chloride (PVC), soft (with phthalate plasticizers, no RoHS exemptions apply)
- various materials requiring flame retardants that are SVHC (no RoHS exemptions apply)

Mixture Category: This category can be used to report the mixture that contains the SVHC, which as a result means the article so assembled contains that SVHC. There are some 200 available mixture categories, most of which don't apply to electronics, while those you may need to be aware of and report include adhesives, coatings, lubricants, and colorants.

Linked Article: A higher-level assembly containing one or more articles as such will need to report this hierarchy as well.

Safe Use Information: This should already be available according to the original REACH requirements, but along with the other items in

this section, it is newly added to the IPC-1752B and C material declaration standards as discussed in chapters that follow.

For now, it's optional to report or not report any of the following data: dimensions, volume, weight, density, and color. One observation is that unless the article's weight is known, the SCIP database will be incapable of determining how much SVHC is being reported on a mass basis.

The goal of further reducing SVHC isn't an easy one, since in most cases there aren't technically viable, much less commercially available, substitutes for many of the SVHC in electronic components. The few exceptions might include PVC, for which some alternate materials are available to avoid additives that are SVHC, and alternatives to halogenated flame retardants used in plastics that aren't SVHC. Besides the potential for RoHS exemptions not being renewed, no longer having to report to SCIP is clearly another incentive to design SVHC out wherever possible.

A count of the REACH January 2026 SVHC list (see Table 2-1) shows the following (counting just the entries for SVHC) containing halogens (fluorine, chlorine, or bromine) and those based on phthalic acid, including the phthalate esters (phthalates).

Table 2-1 The Number of SVHCs Containing Halogens and Phthalates Is SignificantSource: Author data: European Chemicals Agency, 2026

The count is based on the full listing containing multiple rows for related substances. In the year 2026, the count was commonly known as the "253" SVHC list, but within the list are some substance groupings, so that actually the total SVHC count is even higher. (See updates to this frequently changing list later in this chapter.) Regardless of the actual count, over 200 such substances are not to be ignored.

The takeaway for the moment is that just these two categories alone — halogens and phthalates—account for nearly two-thirds of the reportable SVHCs. Finding replacement substances with the same

performance and reliability properties is often not simple, although such replacements will be needed to improve product sustainability.

One Format, Three Ways to Report

The mandated format for SCIP reporting is a dossier, which must be in IUCLID format (see https://echa.europa.eu/support/registration/creating-your-registration-dossier/what-is-iuclid-). This format, designated by the International Uniform Chemical Information Database, is already in use and maintained by ECHA. The data is in XML (extensible markup language), which is a format used for data sharing. It consists of data elements (tags) and the data itself. While the IPC-1752 series of declaration standards are also XML-based, the specific schemas are different from IUCLID.

A client application for IUCLID is available. A user may enter the required SCIP information in a dataset, validate that it meets the criteria for reporting, and create a special zip file called i6z that's suitable to transmit to ECHA.

Rather than perform manual entry, larger companies with many products may decide to collect the information electronically from existing databases, compile it into the specified format, and create the i6z dossier files that way. The final step, which can also be automated, uses the ECHA System to System portal. It transmits the dossier across a web service to the SCIP database itself.

A third option is to use a service provider to collect the supplier's data, filter for items with SVHC, and report directly to SCIP. The choice depends on your company's current environmental data collection method and business model.

Either way, each dossier will need to be validated to ensure it meets the format and content requirements, and when accepted into SCIP, it will create a unique submission number. The IUCLID client itself contains pull-down menus for Article, Material, and Mixture categories. For automated collection and reporting, the same menus are available

as pick lists of valid values. Each has its own numeric identifier code and text, which become part of the XML statements within the dossier.

Getting All the Data: Evolution of IPC Standards

The goal of material declaration standards since the beginning was to facilitate contents reporting (WITS as we have called it) across the entire supply chain, using business-to-business, machine-readable formats. The IPC-1752A Material Declaration Standard has been in use across the industry for years. When the "A" revision had reached the limits of further revisions by IPC governance, a revised standard, IPC-1752B, was published. As with IPC-1752A, the revised IPC-1752B standard defined the XML machine-readable schema for reporting. One notable addition that was needed was the attribute for an article, which is a material specifically formed rather than a raw material whose shape is not important to its function. Significant efforts were put into its initial drafting, revision, and final ballot approval by the Material Declaration Task Force E-31B and its stakeholders to make the B revision a viable means to report to the SCIP database. However, as just described, the IUCLID format was adopted instead. Efforts were taken to harmonize as much as possible with related IPC standards, including IPC-1754 for Aerospace and Defense and Other Industries, and with the IEC62474 declaration standard.

While a full material declaration (FMD) will continue to be very useful as a Class D declaration, the use of the other classes of reporting may also experience an increase in utility, often in combination with Class D homogeneous material declaration. For example, a Class A declaration could directly state whether the item has REACH SVHC or not, while the Class C declaration would offer improved ability to report SVHC at the product level.

As this book is being written, an IPC-1752C revision is being developed. It will be based on JSON (JavaScript Object Notation), a different machine-readable format. JSON (www.json.org/json-en.html) is a lightweight data exchange format. It is easy for humans to read and write. It is easy for machines to parse and generate." This

means that files are not interchangeable (backward or forward compatible); however, the need to update the standard and fully support article data will be of benefit to all in the electronics supply chain.

Conclusions for REACH SVHC and SCIP

The WFD and SCIP reporting requirements will continue to have an impact on electronics manufacturers who already need to manage multiple substance lists (EU RoHS, China RoHS, REACH, California Proposition 65, and so on). New data will be required to be collected and reported, and, for the first time for many companies, reported directly into a regulatory database. Some options do exist for how the data and final dossiers are reported, although the reporting format itself is fixed as IUCLID.

The revised IPC-1752C standard should be very helpful for industry-wide efforts to comply with SCIP, as support for it is rolled out to IT systems and across the supply chain. Always keep in mind that the goal of this additional work is for a good reason—to lead to better management of resources and material selection for a healthier environment and a more sustainable world, at least in the EU.

For Further Reading

R. L. Franz, "New EU Reporting Requirements for Substances of Very High Concern," *Electronic Design*, July 14, 2020. (https://www.electronicdesign.com/industrial-automation/article/21136628/new-eu-reporting-requirements-for-substances-of-very-high-concern)

A Deeper Dive: Learning from Decades of Experience with Material Declarations

With substance restrictions continuing to rise, the IPC-1752A Materials Declaration Management Standard and its revisions help streamline the

design process by providing a standardized format for communicating materials in products across the supply chain.

What you will take away from this section

- How full substance reporting can help manage so many different regulations
- Getting into the details and use cases for different classes of declarations
- An introduction to how Extensible Markup Language (XML) facilitates business-to-business reporting and automation
- Practical examples and best practices

The IPC, previously called the Association Connecting Electronics Industries, is a global trade organization that supports programs to meet the needs of the global electronics industry. Its current name as of 2025 is The Global Electronics Association, and its current direct link is electronics.org. One of its efforts has been developing standard practices for meeting global reporting requirements for information about the materials used in electronic products. In part, this effort has been driven by the RoHS Directive and the Waste Electrical and Electronic Equipment Directive (WEEE). However, due to the growing list of substance restrictions on electronics and other consumer products, companies could benefit from a standard reporting format.

A Journey Toward Data Exchange

Over the past 20 years, the number of worldwide substance restrictions on electronics and other consumer products has grown exponentially. The number of substances on lists like REACH's SVHC in the European Union continues to grow as well—from just 5 in 2008 to over 250 to date and increasing twice yearly (see www.acea.auto/files/GRMS2_chart-1536x864.png and www.acea.auto/fact/grms2-the-global-regulatory-monitoring-system-for-chemical-substances/).

Differing versions of the EU's RoHS Directive are now in force in several Asian countries; the United States is implementing them as well,

with conflict minerals regulations and California Proposition 65. As a result, electronics companies have, out of necessity, become managers of the material content of their products while continuing to demonstrate breakthroughs in performance and features.

Given this "ocean of global regulatory requirements," it's no surprise that standardized reporting has been sought by the electronics industry. Indeed, industry groups and standards bodies have stepped in to fill the need for reporting the contents of electronic goods. Providers of services to support data collection and reporting are on the rise, too.

This is a short list of key industry groups that have helped to standardize full material declarations.

- **Global Electronics Association** (electronics.org): This association was formerly called **IPC,** which remains the brand for its standards.
- **IEC**: International Electrotechnical Commission (iec.ch) is another standards organization.
- **IMDS**: International Material Declaration System (www.mdsystem.com), which, along with its declarable substance list, **GADSL** (Global Automotive Declarable Substance List), serves substance reporting for the transportation industry.
- **ChemSHERPA**: This is a Japan-originated chemical reporting system under the Chemical and Circular Management Platform, CMP (see https://cmp-consortium.com/english).

While compliance is a must-have for companies doing business in regions that apply these regulations, having access to data on the content of products can further support meeting specific customer requirements. It also helps demonstrate conformance to voluntary standards and eco-labels and leads to support for broader initiatives.

It's not surprising that one of the key recommendations of the 2010 NIST workshop on sustainable manufacturing was to "support regulations (e.g., RoHS) with industry standards (such as IPC-1752)."When considering best practices for the transfer of material and substance data across the supply chain, there's no doubt that the IPC-1752A standard has earned its place as one of them. This view is

supported by our own high-volume experience working with a host of suppliers, major customers, and software solutions providers. The other reporting standards listed have their own advocates as well.

Of course, there remain cases where a statement of compliance or yes/no survey fulfills the business needs. Custom spreadsheets continue to be used as well, and many companies demand specific forms from their suppliers. As a versatile reporting means, IPC-1752A supports several different classes of reporting as needed:

- 1752 – Class A: Declaration Query/Reply
- 1752 – Class B: Material Group Declaration
- 1752 – Class C: Material Composition Summary Declaration – Product Level
- 1752 – Class D: Material Composition Declaration – Homogeneous Material Level

A bit of history may help explain our present state of WITS understanding.

History of the PDF Form

When IPC-1752 was first published in 2006, a fillable PDF form accompanied the standard. Many users of the standard asked for the PDF form when downloading its revised version. So where is the PDF form, and why is it no longer available?

After revising the 1752 standard in 2010, the developing standards committee decided to rely on third-party solution (software) providers to develop tools (forms in some cases) compatible with the standard rather than the committee developing and maintaining a form. Further, the old PDF form presented a plethora of problems, compounded by Adobe's inability to support the underlying needs.

IPC-1752A declarations are entirely implemented in XML, or eXtensible Markup Language—an open, non-proprietary language used for years to send data elements and attributes across the Web and between various entities. XML works in a similar way to email. Though there are several email providers, email can be read regardless of the

account or provider. The current XML schema resides in IPC-1751A, *Generic Requirements for Declaration Process Management*. IPC-1751A contains basic demographic, contact, and product information. Therefore, an IPC-1752A declaration must include elements of an IPC-1751A declaration.

The present book is not intended to be a guide to programming, but since the file types mentioned are so important to the sustainability topic and answering the "WITS" question, the data formats should be at least somewhat familiar. From the initial use of fillable PDF forms, material declarations are now evolving from machine-readable XML (Extensible Markup Language) to JSON (JavaScript Object Notation). Two very simple examples may be found at www.json.org/example.html.

The strength of a standard reporting schema is that data can be generated by a supplier, read by a customer company, and then combined with that company's data to further report to its customers. Standardization helps with two fundamental needs: *what* to report (list of substances) as well as *how* to report (format or schema).

How to Report: Large Company Example

A typical use case for a supplier of materials and components is to receive requests from customers to provide full material declarations (FMDs), which will be a Class D disclosure. These requests may be frequent and consist of sizable lists of part numbers to report. They may be specific to certain business units, require some coordination or sharing of responsibility, or be received and handled by a centralized customer support center.

A Class D FMD requires substance-level data to report substances in each homogeneous material to the customer. This data is mandatory, according to the IPC-1751A schema. Passing on the request for FMDs to the company's suppliers (technically, the manufacturers) thus becomes an ongoing business activity. Furthermore, the part on which to report may have its own bill of materials (BOM), both at the homogeneous material and substance levels, as well as at the company part level if the

parent part incorporates other parts. These may be handled nicely by a system that can scale to handle complex BOMs.

Larger companies' needs are best handled by an enterprise software system; today, one can choose from a wide range of systems and options.[5] Given the input of part number and contact information, these systems can quickly generate the XML-formatted files according to the schema specified in the IPC standard. While XML is mainly a machine-readable format, some systems may also provide human-readable form options, such as a spreadsheet or PDF document.

One of the advantages of an enterprise-level system is the ability to input a list of parts and produce multiple disclosures at a time. Further options include the capability of producing stand-alone files that are sent directly back to the customer via email or uploaded to an external loader, or even publishing the FMD on your company's website.

When sufficient materials and substance data are available, reporting via IPC-1752A is efficient and works well. Standardized reporting becomes the key in this scenario. Potential enhancements include additional automation of the process to reduce manual preparation of reports, perhaps initiated by a machine-read request and fulfilled through generation of machine-readable reports. Standardization, though, enables a seamless data flow.

One concern involves keeping all data up-to-date, and of course, doing the arithmetic calculations separately for RoHS homogeneous materials and REACH final article substance concentrations. This means that reporting systems are inherently dynamic and may be complex.

While conflict minerals management has some commonality with other substance data, the reporting format is significantly different from the intent of IPC-1752A. The applicable IPC standard for this regulation is IPC-1755, the Conflict Minerals Data Exchange Standard (see www.ipc.org/IPC-1755).

How to Report: Smaller Company or Service Provider Example

Several options emerge when a dedicated enterprise system isn't a business capability. Free online tools may be used to generate IPC-1752A format XML files from direct keyboard entry, text files, or spreadsheets. In addition, suppliers of this service will perform data collection and reporting for your company. Some overlap does exist between these different solutions and services. The point here, though, is that an IPC-1752A report can be produced in a variety of ways, depending on your business needs and capabilities.

Files conforming to the standard can be output for the customer, as well as serve as inputs. Thus, it fulfills the promise of end-to-end supplier chain substance disclosure.

What to Report

Initially, the IPC reportable substance list focused on RoHS and other substances viewed as potential health or environmental risks. The Joint Industry Guide (JIG) list went through several updates before being discontinued in the latest IPC-1752A standard. The reportable list is now the IEC 62474 database. Since IEC 62474, *Material Declaration for Products of and for the Electrotechnical Industry*, is also a reporting protocol, efforts are underway to continue to harmonize the IPC and IEC standards to have one combined protocol and reportable substance list.

Nonetheless, while standardization efforts continue, it seems every company has a unique reporting list that's more finely tuned to its products, end markets, and customer requirements. Some of these *Declarable Substance Lists* cover mostly hazardous substances, or those from a selection of various watch lists, while others add substances that might be of value for end-of-life material recovery and recycling. There appears to be no immediate end in sight to this aspect of the reporting process. As such, difficulties may arise when the source system (supplier) reports substances that are unknown to the destination system (customer).

Solutions to the custom substance list issue include loading the supplier list to the customer's own system, which isn't a trivial

undertaking, or the supplier manually editing the published files to some degree. Unfortunately, this is a reality that many companies throughout the supply chain must continue to address in order to satisfy customer requirements. 100% reporting of substances is always preferred by the customer, although not always so by the supplier, who is unable to reveal confidential information,

Standards Committee Activities

Let it be known that the development of industry standards requires considerable effort on behalf of all stakeholders. Interested readers are encouraged to engage with electronics.org to help contribute to not only supply chain reporting but any of their other electronics standards in place and under development.

While we do not cover in detail here a similar international reporting standard, IEC 62474, the same comment applies to finding your own national standards organization to participate in the development of International Electrotechnical Commission standards.

In addition to updates and harmonization efforts for IPC-1752A, the E31-b Materials Declaration Task Group had also provided independent evaluation of XML declarations by software solution providers. The purpose of this activity was to provide independent, yearly reviews to validate that these reports follow the latest released standard and schema, contain well-formed XML, and follow the latest lists of substance categories and exemptions.

Companies were invited to submit Class C and/or Class D XML reports, based on a file provided by IPC containing test materials and substances, with selected exemptions. Use of third-party tools to check for well-formed XML and visual inspection of the files were provided by the task group members. IPC is publishing a list of providers reviewed in the first round of evaluation on its website. Note that this activity was a recognition of review of conformance to the standard, schema, and latest substance lists and exemptions—not a formal certification or validation of tools.

Staying Ahead of Regulations: Even More Reasons for FMD

To further explain the expiration dates: these are part of the regulations and trigger regular reviews for current applicability. The exempted applications typically are tightened to become more restrictive in each review cycle.

Having data on the substances in your products will enable risk assessment of expiring exemptions to your business. Clearly, as highlighted in the table, not only commonly used components, but entire product lines like those for telecom and infrastructure products, could be affected by expiring exemptions.

REACH SVHC lists are updated every six months by ECHA, and soon thereafter incorporated in updated appendices within IPC-1752A. In reality, the only way to stay ahead of the continual growth of restricted substances, without continually collecting more data twice a year, is to require reporting of a proactive substance list from your supply chain. It should contain a future "radar" or "crystal ball" list of substances that could likely appear on the next REACH SVHC list. Unfortunately, standardization in this area isn't mature yet, and as mentioned, every company seems to maintain its own custom list of reportable substances.

REACH rules are different from RoHS since there are no exemptions, and the REACH SVHC threshold is 0.1% at the article level, unlike the RoHS threshold applied to homogeneous materials. Also, more than one tonne per annum of REACH SVHC needs to be produced or imported into the EU for action to be required. Because REACH applies to a broader market than just electronics goods, a review of SVHCs vs. their use in your own electronics products is recommended. Importantly for electronics, lead and many lead compounds are now listed as REACH SVHCs.

These substances are there for very good historical reasons, whether electrical performance or mechanical flexibility of otherwise rigid plastics, or reducing the risk of fire and subsequent loss of life or property. Substituting them, as it turns out, is easier said than done.

There are generally very good reasons for having certain substances for performance and reliability. We offer a few examples here.

- Cadmium oxide: used in high-current electrical contacts
- Lead and lead compounds: multiple uses in metal alloys for manufacturing, oxides and compounds in ceramic and glass components, and high-temperature solders
- Phthalates: plasticizer in plastics for flexibility
- Brominated compounds: flame retardant in plastics

Knowledge of these substances to enable taking appropriate action is best enabled by collecting FMD throughout the supply chain. This once again highlights the business value of the IPC-1752A standard and similar standardized methods.

Conclusions and Future Prospects

Standardized substance reporting offers many benefits to businesses. When substance data is fully available, with a system in place to generate FMDs on demand, the reporting process becomes very efficient. Suppliers know their customers' expectations for reporting, and end-customer OEMs gain the benefit of data from the entire supply chain. Intermediate suppliers may use the IPC-1752A for both incoming and outgoing reporting. Intelligence on the content of your products is valuable for assessing risk and taking appropriate action to either report according to regulatory requirements or take steps to design out substances of concern.

Of course, there's always room for improvement in data quality and automation. Some of these areas include the following:

- The ability to generate reports for multiple parts at a time (currently available in some enterprise systems)
- Improved automatic error checking for unlikely data conditions (e.g., multiple RoHS violations in a single part, or exemptions claimed for applications that aren't suitable for the part)
- Direct B2B (business-to-business) request/reply capability, eliminating the need to manually receive requests, generate reports,

and distribute
- Automatic generation of updated declarations when changes occur to part design, or any material aspect of the product
- Automatic publication of disclosures to your company website, facilitating customers or other stakeholders to get the information on demand
- Scientifically based decisions around substance restrictions

Online free tools supporting IPC-1752A XML reporting that have come to our attention may be accessed at the following websites:

- https://ipcgenerator.sourceintelligence.com
- www.assent.com/resources/tools/assent-materials-declaration-tool/

The next section of this chapter repeats some of the same information, which the author believes bears repeating to this day, with the continued value of full material declarations.

Full Material Declarations: Removing Barriers to Environmental Data Reporting

Portions of this section were presented by the author at the 2018 IPC Apex Expo Technical Conference, San Diego, CA, Feb. 26, 2018.

Of the several ways to report substances of interest, many companies utilize FMDs, for example, the IPC-1752A Class D Standard, to stay ahead of new substance restrictions by disclosing product material content.

Effective compliance relies on user-friendly and fully supported software tools that allow suppliers to generate and edit the required XML declaration files. Essential features of these tools include real-time validation of data (like CAS numbers and weight rollup) and the capability to import existing declarations for easy updating.

Yet another major challenge in FMD reporting is the use of non-standard “wildcard” numbers due to the lack of uniformity across

different companies' Declarable Substance Lists (DSLs). Finally, ongoing regulatory complexities, such as the "Once an Article, Always an Article" (O5A) principle for REACH SCIP reporting, will ensure the continued importance and evolution of robust FMD standards and their supporting database and software tools.

Here we focus on requirements for tools that enable rapid and accurate reporting of Class D FMDs that can be used by suppliers primarily at the base of the supply chain (e.g., raw materials and smaller components). Examples of how this data can be used by the supplier's immediate customer to build more complex FMD data for product-level assemblies are also provided.

Why Take the Road to FMD?

One of the advantages of the FMD approach is that it's the only way a company can stay ahead of the ongoing addition of regulated substances. RoHS has been relatively static in this regard, with the first set of six restricted substances officially published in 2003 (see https://eur-lex.europa.eu/eli/dir/2002/95/oj/eng) and staying the same until four additional substances called phthalates came into force for most equipment types in 2019. Other than that, FMDs have remained a strong solution to WITS and ensuring RoHS compliance.

REACH, promulgated by a separate agency, ECHA, is much more dynamic and adds new substances of very high concern (SVHCs) to its Candidate List roughly twice a year ever since 2008. The history is all maintained by date at https://echa.europa.eu/candidate-list-table.

Note that there is some double counting in the data, since a few of the substances were listed a second or third time due to different toxicological reasons. This may be significant in some cases since the toxicology of a given substance may require updating a given Safe Use statement. For reference, these are the possible reasons for including a substance in the SVHC list, and a given substance may be associated with one or more of these categories.

- Carcinogenic
- Endocrine-Disrupting Properties
- Mutagenic
- Persistent, Bioaccumulative, and Toxic
- Respiratory Sensitizing Properties
- Toxic for Reproduction
- Very Persistent and Very Bioaccumulative

It is worth mentioning that useful information about the Standard and its implementation and advantages may be found on the IPC "Data Exchange Standards" web page (see www.ipc.org/ContentPage.aspx?pageid=Materials-Declaration). Additional advantages of FMD have been published, for example, by companies offering such services, companies needing FMDs from their suppliers, industry conferences, and articles in electronics journals. The story continues, and the message remains clear: Companies need a way to stay ahead of the growing list of new substances they are required to manage. FMDs are the best way to do so.

Requirements Part One: The Schema is the Roadbed

In the next sections, we list and explain the value of functional requirements that a good, basic FMD reporting tool should have. At the most basic level, the tool by its nature will be software, and to be used for reporting up the supply chain, the XML declaration file must conform to the IPC Standard itself.

Between approximately 2014 and 2017, the IPC 2-18b Materials Declaration Task Group members offered their time and expertise to help review, on a blind submission basis, XML files including Class D FMDs. Using software tools that are available for checking conformance to the schema as specified in the Standard, as well as a review by IPC 2-18b participants, those software solution providers at that time were verified to conform to the basic requirements of the Standard. It is worthwhile noting here some of the best practices to review

conformance to a schema-based standard; these tools may be needed again from time to time when the schema changes.

The following summarizes FMD best practices.

- All mandatory data elements (tags) are present, which must be completed when entering data into the tool, if not already present from some prior data entry or load. These elements include data like supplier and customer IDs and part numbers, and homogeneous materials in the product broken down by substances and their weights.
- Ability to enter the most useful optional data elements as desired, or as requested by the customer. For example, substance weight is mandatory, but concentration is optional.
- Ability to incorporate a legal statement, either with a standard boilerplate or by entering a custom statement.
- Tags identifying the data as Class D (FMD) based on substance reporting at the homogeneous material level; Class C substance category reporting at the product level; or Class A Query/Reply format (true/false compliance statements).
- Further details, including a complete list of Mandatory and Optional data, may be found in the IPC-1752A standard and its successors.

Requirements Part Two: Lanes of Chemical Data

Since FMD is all about the chemical data, and suppliers in the electronics industry may not have extensive chemical expertise, this set of functionality is critical to generating Class D XMLs as correct and error-free as possible. Clearly, to even begin generating FMDs requires having the product's chemical composition data, and unfortunately there's no magic to manage this complexity other than a materials and substances database or spreadsheets to manage the list of ingredients to be reported.

Some of the major computer-aided design (CAD) systems are offering functionality to select raw materials from a database coupled to the CAD system, which is logical since the designer is specifying the materials in the first place. One potential roadblock here is that product

design engineers may be focused on the engineering bill of materials (EBOM), which is the as-designed configuration. When it comes to manufacturing the product, the manufacturing bill of materials (MBOM) may look different due to differences in how in-process or stocked subassemblies are handled, and may include more information on the raw material and component suppliers than the EBOM. And while regulations like RoHS are specific to the electrical/electronic product, other regulations like REACH include non-electronic items like documents and packaging. Resolution of these differences will likely be company-specific and depend greatly on the software systems in place.

Next, we briefly highlight important functional requirements for any tool used to generate FMDs from materials and substance data.

The ability to select substances from a list by CAS number prevents errors, since the CAS number is a key for many receiving systems and is the Authority tag specified in the IPC standard. A CAS number lookup list should be provided in the tool, which has the advantage of speeding up data entry and selecting matches quickly from valid selections provided by the tool. The tool may also validate the format of the CAS number itself, which must be 10 digits separated into three groups by hyphens, with the last digit being a check digit. These rules are published by the Chemical Abstracts Service (CAS) at www.cas.org/content/chemical-substances/checkdig.

This type of validation may be useful to allow newer, valid CAS numbers that aren't in the lookup table to still be entered. The problem of "wildcard" or declarable/reportable substance lists will be covered in the next section, since it remains a problem in the industry.

A lookup of substance names can also expedite entering substance data, again by ensuring that a valid substance name is used, and a valid CAS number goes along with it. The advantage is that a substance name may be more easily recognized and used by a human than a CAS number. This approach to validation has the disadvantage that compounds and even pure elements may have many different synonyms, in which case the direct CAS number lookup would be more useful.

The input screen for materials and substances data may be a spreadsheet, formatted to list all substances and their mass percentage under each applicable homogeneous material. This kind of table is the heart of an FMD, where each material is composed of its constituent substances, all with reported weights in the product. Optionally, data such as attachment files and concentration ranges may be accommodated. If exemptions apply at the material level, they must also be selected, and the final declaration published in IPC standard formats.

Requirements Part Three: The Wildcard Detour

By necessity, companies and standards organizations themselves have used Reportable or Declarable Substances Lists for years. One of the early lists was the Joint Industry Guide (JIG), which went through several updates. Amendment 3 to IPC-1752A includes the following statement: The IEC 62474 database of restricted and declarable substances replaced JIG in January 2014.

Meanwhile, most companies have created their own DSLs so that they will receive:

- Data on those substances currently with regulatory restrictions
- Data on industry-specific substances
- Data on other substances the company's customers expect to know about
- Substances that are not yet under any regulatory restrictions but could be at some future date.

This latter case is exactly the REACH situation shown at the beginning of this paper. While there are some ways to get advanced information about the next substances to be added to REACH, these are not usually foolproof. Therefore, companies tend to cast a rather wide net to ensure future substances are included in their suppliers' declarations.

The IEC62474 database (http://std.iec.ch/iec62474), as of this writing, was most recently revised on June 25, 2025. Many

companies have nonetheless found it necessary, for the reasons listed, to develop more comprehensive lists of their own. Without mentioning specific company DLSs here, a general review of some of the many that are used in the electronics industry shows two basic trends:

Substances listed in common as a core set of substances, including those in common with the IEC62474 list.

Substances that are less frequently found and not part of a common core list

Since homogeneous material reporting is at the substance level, with authority being the CAS number, this presents a data-handling/segregation dilemma.

In a good reporting tool, then, some accommodation must be made for accepting these "wildcard" substances that inherently have no CAS number. We have seen that a commonly, but not universally, accepted limit of 10% per homogeneous material can be checked in the tool to ensure this limit is not exceeded. A good tool should also allow for a choice of a customer-specific wildcard substance name, which is not subject to checking from a CAS number list or a CAS format validation routine. Based on our review, if proper warnings are provided, this appears to be the best way at present to handle such data.

Requirements Part Four: Fewer Barriers, More Open Road

In this section, we have presented benefits from FMDs. Future developments like Agentic AI may reduce the reliance on manual keyboard data entry. Meanwhile, utility may be realized through the ability to revise, reuse, and build on data once it has been initially entered into a tool or larger system.

The first of these utilities is the ability to quickly edit the substances in a material or component. For companies making a family of items with related composition, changing just a few entries, or modifying the percentages of them, can be done in seconds and saved under a different product name and XML file, with version tracking as desired in the file name.

Once a complete XML FMD is generated, productivity is enhanced if that file can be easily imported again at a later date and edited as required. This portability and flexibility of data allows a supplier further down the supply chain to utilize a growing library of common materials and their formulations, and to quickly create new ones without having to repeat some or even most of the data entry. In most cases, the company's own information, like company ID, contact, and authorizer, will be repeated over many declarations. If the contact and authorizer are the same person, they could be copied directly with a choice in the tool.

While we are focusing here on the Class D FMD, the ability to generate Class A or Class C FMDs or declarations at the same time may be useful. These should be selected or deselected as desired, or as required by the customer. Class A query/response answers should be straightforward, as should selection of exemptions from a list. Similarly, the substance data in the Class D data section should be easily edited to enter fresh data while retaining the rest of the information already entered.

Interactive help should provide guidance to first-time and infrequent users. Checks along the way improve speed and accuracy without having to consult a user's manual, which incidentally should also be easily accessible for those who wish to read the instructions first. Finally, the tool should prevent hang-ups and errors. Support services should be provided, and a process to investigate and resolve bugs, or perceived bugs, should be easy to submit and provide timely responses.

At the end of data entry, there should be a final validation of the XML, ensuring that mandatory information has been entered, and the weights of substances add up to each homogeneous material being reported. These checks help ensure that the XML will successfully load to the customer's system.

Conclusions: To the Superhighway

According to some observers, FMD still has too many barriers to really catch on. We disagree. Supply-chain reporting has to begin somewhere, by providing data to middle supply chain companies, and so forth up the chain to the OEM. FMD is the only reporting approach that helps to minimize the ongoing burden of keeping up with the ever-growing lists of regulated substances and expiring exemptions.

It has been mentioned that the IEC 62474 database is now invoked as the reportable substance list in IPC-1752A Amendment 3. In addition, the development of an IEC 62474 international standard for reporting is in process, which will also specify an XML format. Work is underway to harmonize the schema of both IPC and IEC standards via communication and common participants in both IPC and IEC standards development, but differences should still be expected. Development of the IEC reporting standard nevertheless underscores the interest and need for FMD realization in XML format.

Further enhancements can also be realized in the future. Here are a few:

- Integration with manufacturing data for mixed, compounded, or formulated materials.
- Availability of integrated materials selection with design tools for more complex products.
- True business-to-business methods to request data as well as provide data all in standard machine-readable formats.
- Enhanced error checking, validation of common-sense rules, and agreement between, for example, a Class A declaration that says RoHS Compliant = True, yet the Class D file for the same item reports a RoHS substance over the threshold percent.
- Support for updated guidance from ECHA on Once an Article, Always an Article, which changes substance percent reporting from any top-level assembly to the lowest-level Article exceeding the 0.1% SVHC threshold. It's becoming clear that this will require a new data attribute to flag Articles, as distinct from unshaped Materials or Complex Objects. It's our understanding that this will be considered in the development of a revised IPC-1752B Standard.

In addition to the motivation to stay ahead of the growing number of regulated substances, business processes and procedures that support FMD can also be useful. The expectation that FMDs must be provided can be a requirement for gaining new business or for qualification of an item as a prerequisite to be purchased. A company can also include FMD responsiveness in ongoing supplier evaluation performance ratings that may influence awarding future business. Once an FMD is received in a well-formed XML format, loading this data to the customer system can be automated for maximum efficiency and reused through the FMD cascade process. We have seen it work and only need more FMDs entering the road.

Key Takeaways

This chapter has introduced the very important key to understanding WITS that just a few decades ago did not exist: material declarations. Thanks to the development of machine-readable data, business-to-business reporting is now widespread across the electronics supply chain from raw materials to components to finished products. Using this data to understand and take action on what has been reported, while clarifying the good and bad from a sustainability perspective, is the subject of the next chapter.

For Further Reading

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3. Contents: Hazardous or Useful?

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An old proverb says that one man's trash is another man's treasure. This is true in the world of electronics, since some contents may be hazardous but not worth much economically once bound into complex hardware. Others may be both useful and valuable enough to recover later. Our work here is to be able to tell the difference. Understanding the historical reason for the use of a given substance that we now know is less than desirable is a start, but typically a simple drop-in replacement will not be easy. To build our story out to the future, chapters after this one will help you understand some upcoming new sustainable material choices, how more reliable and long-lived products help improve sustainability, followed by several approaches to help make improvements possible.

Now that you know more about WITS, in this chapter, you will learn about these important electronic materials. A comprehensive encyclopedia of the nearly 100 chemical elements and almost unlimited number of materials made with them would not be possible here, so we see the discussion of several of importance to making electronic products.

- Lead
- Copper
- Gallium
- Halogens and Phthalates

- Plastics

Given these representatives of problems and opportunities in important electronic materials, this chapter begins with a perspective of the heavy metal, lead.

Lead: Past, Present, and Future

What you'll learn in this section

- Lead has been used by humans for millennia and remains critical for today's electronics.
- When effectively managed, lead can continue to play an important role in avoiding possible harmful environmental and health consequences.
- Replacing lead is not easily accomplished in many applications while retaining the same performance and reliability.

Heavy History

The element lead has a long history of use, sometimes with bad outcomes due to its toxicity when ingested, for example, in drinking water. Lead is also a vital constituent of today's electronic components, solders, batteries, photovoltaics, and metal alloys. Here we provide some perspectives about past, present, and future use of lead and how we may control its distribution around the world. Improvements in the life cycle of lead are needed to conscientiously manage the use of this unique element where it's needed to perform critical functions, while preventing unintended consequences when improperly released or discarded into the environment.

Lead has been used for over 5,000 years. Its desirable properties include a low melting point compared to other metals, an ability to be ductile and malleable, and its utility in a variety of alloys such as brass and solders. In ancient times, alchemists associated lead with the planet Saturn, and the two even shared the same symbol, highlighting how lead has been part of history for millennia.

From a modern perspective, lead is in the same periodic table group as carbon, which is the basis for life as we know it, yet lead is toxic to life itself. In between the two lie the elements germanium, silicon, and tin, whose relationship is discussed in the final chapter.

Lead vessels and pipes were used in the days of the Roman Empire, and although not conclusively proven to be the reason for the Empire's collapse, the Romans' pervasive use of lead and the Empire's later fall continues to this day as a cautionary tale for how lack of attention to where lead is used can cause problems. More recently, the use of automotive gasoline containing lead anti-knock compounds peaked in the 1970s and has since declined, with lead-free gasoline now being burned by unleaded gas-compatible engines. In the meantime, lead and lead compounds were deposited from vehicle exhaust in unsustainable amounts near roadways.

While lead poisoning doesn't often cause death anymore, the greatest concern today is childhood poisoning that seriously affects mental development. Drinking water with high concentrations of lead has been headline news in recent years.

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Issues related to lead in municipal water supplies aren't highly technical at all; they're about archaic and aging infrastructure,

plumbing, and, to some extent, the result of social injustices because these shortcomings occur more often in poor and neglected communities. At minimum, measures like the United States' Safe Drinking Water Act of 1974 need to be maintained rather than relaxed, with resources provided for enforcement.

The high volumes of discarded electrical and electronic equipment (EEE), in particular, have resulted in regulatory restrictions and recovery requirements, led by the European Union and adopted in other countries and states like California. Here's a short list of the regulations relevant to EEE:

- European Commission (EC) Directives: RoHS, Restriction of Hazardous Substances; WEEE, Waste Electrical and Electronic Equipment; ELV, End-of-Life Vehicles
- European Chemicals Agency (ECHA) Directives: REACH, Registration, Evaluation and Authorization of Chemicals, specifically the Candidate List of Substances of Very High Concern (SVHC)
- Proposition 65: California Office of Environmental Health Hazard Assessment

These laws operate at several levels: to ban the use of certain toxic substances, including lead and its compounds, while allowing exemptions for specific applications where there's no alternative but subject to periodic review (RoHS); reporting to the public on safe use of substances of very high concern (SVHC), including lead and selected lead compounds (REACH); and setting collection and recovery targets for electronic waste (WEEE). Similar legislation applies to end-of-life vehicles (ELVs). Proposition 65 in California further requires a warning label on products where lead or certain lead compounds pose a risk of exposure.

These regulations all drive a reduction in the use of lead and toxic substances in the first place. Moreover, they prompt total life cycle considerations with environmentally sound, long-term goals of a circular economy and closed-loop material flows.

Lead in Electrical and Electronic Materials and Components

Why do we continue to need lead? One reason is history: the materials available to make electronics were never designed for sustainability. In electronics, lead is used in metal alloys, glass and ceramic components, and solders. Some applications, like piezoelectric components that convert motion to electricity, have used lead for over 70 years. It is time to rethink how these devices are made.

Besides electronics, one of the major uses today is the lead-acid storage battery. Lead is the material of choice for X-ray shielding and has smaller but critical usage in other high-technology applications.

Several critical uses of lead are allowed up to specific limits in a few important electronic applications, for compliance with the EU RoHS Directive. Notably, these exemptions come up periodically for renewal (see September 8, 2025 update). The actual legislation is more complicated than listed here in terms of specific usages, but the examples given have broad applicability to electronic products produced in high volume. Rather than copy all the details here, which may soon become out of date, only the broad categories of each series of exemptions are listed. The message is that these are unlikely to expand, but rather to continue to become more restrictive or be discontinued altogether. New generations of products need to be aware of this fact and seek alternative materials.

The RoHS exemption series for lead includes the following broad categories, which are subject to continual review and change to further restrict their use.

The existence of such regulations highlights the lack of awareness and action decades ago. Preparing for change in next-generation electronics will not happen overnight.

- 7(a) High temperature solders
- 7(c) Glass and ceramic components
- 6(a) Steel
- 6(b) Aluminum

- 6(c) Copper

RoHS exemptions all have a predefined review date, at which time a decision will be made by the European Commission to continue or modify the exemption, or render it expired and no longer active. Specific categories of equipment may have their own dynamic regulations. Some of these include many familiar types of goods containing electronics.

- Large and small household appliances
- IT and telecommunications equipment
- Consumer equipment
- Lighting equipment
- Electrical and electronic tools
- Toys, leisure, and sports equipment

Lead provides the important property of allowing certain alloys of copper, aluminum, and steel to be machined. Copper specifically is used widely in electrical connectors, while aluminum and steel may also be employed in electronic products.

Solder is critical to electronics assembly. Prior to the restriction of the original RoHS Directive, the solder alloy of choice for most electronic assembly, eutectic 63/37 tin/lead, was largely replaced in many markets, even outside of the European Union, for compliance by 2004. Higher-temperature solder requires much higher concentrations of lead, typically greater than 85%. These solders are critical to applications like two-temperature reflow assembly and in high-temperature applications where the lower-melting eutectic solders are inadequate for performance and reliability.

High-temperature solder is used in modules and hybrids and to provide internal connections in high-temperature relays. Other familiar components that may use high-temperature solder internally include die attach in power semiconductors and in potentiometers and capacitors.

Lead in glass and ceramic components provides important properties for sealing and adhesion, mechanical strength, and overall

reliability. Familiar components of this type include sensors, transducers, and chip resistors. For piezoelectric devices, lead zirconate titanate (PZT) is the most commonly used material for ceramic resonators, and sensors and transducers, including audio alerts and ultrasonic devices.

There's a severe lack of suitable substitutes for lead in machinable metals, high-temperature solder, and glass or ceramic components. Recent work by multiple industry task groups has found that in most cases, there currently are no viable replacements for current uses of lead. These findings are independent of material cost concerns, since substitutes for the performance of lead and its properties are simply not known yet, while any possible substitutes may bring drawbacks of their own. Detailed technical dossiers are being submitted to the European Commission for extension of the RoHS exemptions for lead.

Lead metal and 17 specific lead compounds are also listed as SVHC under the REACH Directive. While this isn't a ban or restriction, it does require public reporting when such substances are present in >0.1% by weight of the article. Again, their use is based on critical need for performance, which in the case of piezoelectric devices provides the fundamental interaction between electric charge and mechanical stress that makes them so useful. Besides lead metal, these four lead-oxide compounds are categorized as SVHC and are commonly found in small amounts in components made of ceramics and glass:

- Lead monoxide
- Lead tetroxide (orange lead)
- Lead zirconium trioxide
- Lead zirconate titanate (PZT)

Refer to the Directives themselves for up-to-date information as listed next in their respective languages (see https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202501802).

Future Use and Prospects for Lead

While the review of current lead usage and research on alternatives continues, new technology is finding utility in lead to assist with the growing need for sustainable energy. For example, lead in the form of perovskites, which is a specifically defined crystal structure that may be based on lead iodide, is one of the promising materials for the rapidly developing photovoltaic industry.

Lead is a naturally occurring element, unlike synthetically manufactured compounds. This fact distinguishes the life cycle of lead vs., for example, certain flame retardants and dielectrics, two groups of which were banned by RoHS in 2004. Substitutes were found, but concern still remains about whether their long-term effects on the environment are fully understood.

In the case of lead, which is found in nature, what's needed is more environmentally benign mining, controlled use in manufacturing to prevent unwanted releases to workers and the environment, and collection and recovery from end-of-life products to close the material loop.

Today's lead recovery efforts are dominated by processes built to recycle used lead-acid storage batteries. For other types of consumer electronic equipment, the phrase "Urban Mining" has been coined to describe the ability to obtain value from large volumes of discarded consumer goods.

These reclamation efforts target high-value metals, notably copper and the precious metals gold, silver, platinum, and palladium, while other metals, like lead, kind of go along for the ride with discarded goods and are collected for recycling. Still, the high-volume recycling of metals, including lead, is thus becoming more of a circular economy as it should be.

To comply with the original RoHS and for global manufacturers who themselves have adopted the same requirements, the move away from eutectic tin-lead soldering of printed circuit boards and component terminations in the early 2000s has reduced the lead content in electronic products. As fully electric vehicles continue to rise in market share, the use of lead-acid batteries—no longer needed to start the

absent internal combustion engine while other battery technologies like lithium-ion are used instead—will decline as well. Lead may fade but not disappear.

It remains to be seen how the promising lead-containing perovskite photovoltaic technologies will grow in the future. If these new applications of lead grow significantly, recovery and recycling flows for lead will need to be further developed.

Lead Recovery and Recycling

Recovery of lead is well established, with metal smelting operations using both as-mined ores and end-of-life product recovery streams as feedstocks. The inputs for these operations need to be dynamically adjusted according to feedstock availability and composition. Discarded leaded-glass cathode ray tubes from televisions and monitors are a sub-specialty with volumes that have recently peaked in end-of-life treatment. They should also decline in the next few years with flat-screen technologies taking over the display market.

While specialized usage of lead can't currently be substituted or replaced for the listed electronic applications, a conscientious effort should be brought to bear by both industry, governments, and informed consumers to further improve closed-loop recovery of lead. For all sectors where lead is still required for product functionality, recovery and life cycle management rather than discarding as waste is key. As automotive lead-acid battery volumes decline, we need to ensure that newer lead-containing PV technologies are built out with closed-loop material recovery already planned in.

Once recovered products have entered the recycling process, which in most cases will be a dedicated metal smelter or combinations of secondary and primary smelters, these operations should adhere to best practices for environmental safety. Newly mined ore is generally one of the feedstocks, which in the case of lead is typically galena, or lead sulfide.

Various regulatory agencies publish guidance on Best Available Technique, sometimes called Best Available Technology, and related

documentation such as Best Available Control Technology, for mining and metal recovery and refining operations. Adhering to these guidelines means that both ore mining and metal recovery have practices in place to control emissions of dust and other airborne releases, scrubbing of sulfur rather than releasing sulfur oxides to the air, containing such operations in closed systems, and using energy-saving practices like heat recovery.

While these recycling operations still carry some environmental footprint, best practices specifically defined for lead ensure that the recovery of refined lead back to the stream of commerce is done responsibly in a closed loop. Lead and other metals can be recycled virtually without end, unlike other materials like paper and plastic, whose performance degrades in the recycled output.

Outside of the industrial sector, a broad interdisciplinary effort including public and private health awareness and action is still needed to recognize and address basic flaws in water delivery to worldwide populations. In addition to the lead used in old paint, these problems with lead probably have more public awareness than the uses in electronics discussed here.

New science and high technology aren't critical to fix corrosion in lead-containing pipes and aging infrastructure. We only require determination to do so. Controlling the distribution of lead globally, including life cycle management of end-of-life electronics, will ensure lead is kept out of drinking water supplies in the first place. In fact, this even older quotation from Benjamin Franklin is still sound advice: "A place for everything, everything in its place."

We end this section with these final recommendations.

- To the electronics designer: Be aware of existing and future environmental regulations and seek to replace substances like lead wherever possible, while considering overall life cycle impacts as well.
- Be a responsible citizen with your own unwanted electrical and electronic goods and support the development of electronics reuse and recovery streams wherever possible.

- Encourage sustainable practices in your home office or where you work, wherever electronics are found.

For Further Reading

Delegated Directives (EU) 2025/1802 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202501802)

Delegated Directives (EU) 2025/2363 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202502363)

Delegated Directives (EU) 2025/2364 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202502364)

US Geological Survey, National Minerals Information Center (https://www.usgs.gov/centers/nmic/lead-statistics-and-information)

International Lead Association (https://ila-reach.org/)

R. L. Franz, "Lead: Past, present and future," *Electronic Design*, Jan. 28, 2020. (https://www.electronicdesign.com/industrial-automation/article/21121514/lead-past-present-and-future)

Copper: Conductivity Benefits and Environmental Impact

Unlike lead, which is a known neurotoxin, copper is recognized as an essential trace mineral in the diet. Electronic products today would not be possible without copper. Your house wiring is likely made of copper, and smaller amounts are critical to circuit boards and many components. Here, we discuss copper's vital role in electrification, its impact on the environment, and emerging alternatives like carbon nanotechnology.

What you'll learn in this section

- Copper's role in clean energy initiatives
- Issues with copper mining
- Possible alternative materials to copper
- Copper and the circular economy

Most circuit designers probably aren't thinking about, much less worrying about, the metal copper. But as the electrification of the world continues, copper conductors used in applications from microchips, other components, and circuit boards, to household, industrial, and automotive wiring, and critical workhorses like batteries and electric motors, point to the need to spotlight its starring role.

This section is mainly informative, but you can take some actions in your professional and personal life to help manage this important material.

Critical Minerals and Copper's Role in Clean Energy

We begin with a pair of quotes from the International Energy Agency (IEA), as copper, lithium, nickel, cobalt, and rare earth elements are essential components in many of today's rapidly growing clean energy technologies—from wind turbines and electricity networks to electric vehicles.

> "Lithium, nickel, cobalt, manganese, and graphite are crucial to battery performance. Rare earth elements are essential for permanent magnets used in wind turbines and EV motors. Electricity networks need a huge amount of aluminum and copper, the latter of which is the cornerstone of all electricity-related technologies."

One of the limiting factors in the use of copper is actually the ability to get enough of it. The growing need for energy-critical materials, as well as other global factors, means that ongoing supply capacity may face risk. Four such risks have been estimated by the IEA in a lean energy transition risk score for key energy transition minerals. (See

www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Energy%20supply&indicator=TESbySource.)

- Supply risks
- Geopolitical risks
- Ability to respond to disruptions
- Exposure to ESG and climate risks

ESG refers to Environmental, Social and Governance (see https://marketbusinessnews.com/financial-glossary/esg-definition-meaning/), which may affect reporting and compliance with regulatory requirements, including the financial well-being of a company. So, it's good for electrical and electronic professionals to have some basic familiarity with this growing trend.

Although we are discussing copper here, similar risks that exist to different degrees complicate the sustainability picture of other minerals, including cobalt, lithium, nickel, graphite, and several of the rare earths. (You learn more about rare earths in Chapter 7.)

Where Is Copper Found?

As geochemistry would have it, copper is widely distributed across the globe. The largest production of copper is in Chile, followed by a dozen other countries, including Peru, Congo, China, the United States, and Russia, and several other main producers. (See https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-copper.pdf.)

To emphasize the worldwide distribution aspect, the number two producer is all of the other countries not specifically named. This may be seen as some good news, helping to reduce the risk factors by spreading supplies out globally.

Environmental Impact of Copper Mining: The Issue of Mine Tailings

Mining metals isn't a clean process. Most of these operations will leave large amounts of excess material known as tailings, of which there are as many as 18,000 such dumps worldwide.

These may be in the form of a slurry or sludge that's retained in ponds typically contained by earthen dams. Failure of these dams leads to uncontrolled, massive spills containing toxic metals and other substances. When this happens, millions of gallons of the tailings are released, contaminating downstream water.

Even when such disasters don't occur, the tailings may dry out and release the toxins as fine particles into the air. Let's be clear by noting that dust containing metals like zinc, lead, antimony, and arsenic is unfit to breathe, especially for small children.

Regulating such tailings is difficult at best and further compounded by the fact that many sites are so old that ownership isn't clearly defined. This is an example of an outdated last-century industrial practice that didn't properly consider or effectively deal with the long-term effects of operations and their impact on the environment. They were pushed aside as someone else's problem or simply ignored.

Possible solutions to avoiding the problems of tailings, as discussed next, include increased recycling of already mined and refined copper and developing nanotechnologies like those based on carbon rather than metals.

Potential Copper Alternatives in Electrical Applications

It has been suggested to consider more abundant metals, including iron, aluminum, and magnesium, as possible alternatives for copper. It doesn't seem likely, however, that this will become widespread or even necessary in the near future.

While the engineering, supply, and cost considerations are complex, it's easy to see why copper is so often the conductor of choice because it is a very good conductor but less expensive than silver. In terms of conductivity, expressed as Siemens per meter, the list goes like this

from best to worst: silver > copper > gold > aluminum > tungsten > zinc > nickel > iron > platinum > tin. Each of these has its own particular benefits and corresponding applications, to which we propose to add carbon nanotechnology in upcoming sections of this book.

Though the other metals are generally considered conductors, their other properties and greater resistance losses aren't desirable in most cases as a main choice. Still, they may fill niche functions within a component or system. Zinc is commonly alloyed with copper to make brass used in connectors, and/or with tin to make bronze, while nickel and tin are commonly found in component terminations in addition to the precious metals. (See https://sciencenotes.org/table-of-electrical-resistivity-and-conductivity/.)

Not listed in this table of metals is another developing alternative in the realm of nanotechnology where carbon nanotubes and graphene are seeing development and growth. The conductivity of these materials is not only competitive with, but may even exceed, the conductivity of copper. Cost and availability concerns remain high at the present time, but the reader is encouraged to be aware of this upcoming technology.

One of the possible environmental benefits of carbon-based technology (see www.annualreviews.org/content/journals/10.1146/annurev-matsci-010622-105440) could be the abundant availability of starting material since the element carbon is within us and all around us. And, while the materials must be manufactured, unlike metals, they require no mining with its resultant tailings. Resolving the basic conflict of needing both metal conductors and carbon-based insulators from raw materials to end-of-life recovery may go a long way toward future sustainability.

Copper's Role in the Circular Economy

Plainly stated, combustion engines consume fuel and burn it to carbon dioxide, water, and various undesirable side products. Metals like copper, which power the world with electrical energy, aren't consumed

but rather remain in use for years, after which they may be recovered, recycled, and reused over and over.

This fundamental difference is one of the drivers of broad initiatives like that of the European Union's "Circular Economy" (see www.science.org/doi/10.1126/science.ads4702). This builds on the existing WEEE Directive (Waste Electrical and Electronic Equipment) that requires diversion of such equipment from landfills and incineration to a closed material loop.

From a more technical perspective, guidance like the series of European standards EN 50625 Collection, Logistics & Treatment requirements for WEEE (see https://standards.globalspec.com/std/9914895/cei-en-50625-1), and its technical specification 50625-5 (see www.iea.org/topics/critical-minerals) specifically address copper and precious metals in electronics.

Conformance requires that 100% of copper, gold, silver, and palladium be collected as inputs to recovery, with a minimum 90% resulting yield for all four metals. These metals can then be returned to the stream of commerce and merged with newly produced metal to continue new product production.

Other parts of the 50625 series of standards are specific pretreatment of lamps, CRTs and flat-panel displays, temperature exchange equipment containing refrigerants, and photovoltaic panels, which should be of particular interest if working on those products. (Links to the full standards cannot be provided here since the documents must be purchased from the owning organization or authorized publisher.)

Closed-loop product life cycle thinking isn't new to the electronics industry since regional collecting, recycling, and reuse of electronic consumer products has been practiced for several decades. The current Environmental Protection Agency (EPA) guidance (see https://pubs.rsc.org/en/content/articlehtml/2021/gc/d0gc04430j) calls this a "donation" rather than mandatory collection.

Recycling organizations like e-Stewards (e-stewards.org) provide certification for recycling operators who conform to best practices, with a searchable index of global recycling companies by region. Your local solid waste authority may also offer such services, for example, drop-off locations or scheduled curbside pickup of WEEE.

From a practical perspective, your copper and similar metals would most likely fit under one of the scrap categories of the Recycled Materials Association (ReMA) (see www.electronicdesign.com/author/Roger-Franz), such as circuit boards and shredded circuit boards from the processing of end-of-life electronics. More along these lines may be found in later chapters.

That copper is a most capable electrical conductor isn't news, but hopefully the insights on its origins, side effects, and environmental life cycle impacts have been interesting and useful to you. We conclude with these takeaways:

- Copper is an important contributor to the overall circular life of electronics.
- How our professional work impacts the environment deserves to be more widely understood.
- Alternative conductor materials based on carbon nanotechnology are being developed.
- You can use this information in your daily life when you recycle rather than dispose of your obsolete or nonfunctional electrical and electronic equipment.

For Further Reading

R. L. Franz, "Copper: Conductivity benefits and environmental impact," *Electronic Design*, Aug. 20, 2024. (https://www.electronicdesign.com/technologies/industrial/article/55134576/understanding-coppers-electrical-conductivity-and-environmental-impact)

Penny for your thoughts. Now for a spotlight on another unique metal, gallium.

Enter Gallium

In this section, we detail the somewhat lesser-known but very unique metal, gallium. You have no doubt seen (more or less directly) gallium used in a light-emitting diode (LED), which is familiar in many types of products and lighting in general. (See https://pixabay.com/photos/yellow-led-light-emitting-diode-3358207/.)

Gallium has been used for years in the form of gallium nitride. (See S. Nakamura and M. R. Krames, "History of Gallium–Nitride-Based Light-Emitting Diodes for Illumination," in *Proceedings of the IEEE*, vol. 101, no. 10, pp. 2211–2220, Oct. 2013. Available at https://ieeexplore.ieee.org/abstract/document/6582668).

GaN is one of the emerging electronic materials for applications like optical and high-frequency devices. Whether it will be sustainable has yet to be fully determined.

Gallium is a key element in photovoltaic (PV) cells based on copper indium gallium selenide (CIGS) and GaInP. (See M. Yamaguchi, F. Dimroth, J. F. Geisz, and N. J. Ekins-Daukes, "Multi-junction solar cells paving the way for super high-efficiency," J. Appl. Phys., vol. 129, no. 24, Art. no. 240901, Jun. 2021. Available at https://pubs.aip.org/aip/jap/article/129/24/240901/523212).

These panels are much greater in area than microwave chips or LEDs, with proportionally greater material demand. And the deployment of PV cells continues to grow in the quest for clean, renewable energy. While the energy grid is not our main focus here, electronics consume energy, and sustainable electronics, from an energy perspective, is discussed in Chapter 4.

(see https://pixabay.com/images/download/mrganso-photovoltaic-system-2742308_1920.jpg/).

What Is Gallium?

Gallium (Ga) is a unique metal used in making many types of electrical and electronic products perform efficiently. Though used in small amounts, it's still a limited resource. You have no doubt heard "reduce, reuse, and recycle," and over the past few decades, significant progress has been made in the recovery of electronics "end-of-life" products. While many of the metals used in electronic products have now achieved significant levels of recycling, such is not the case for minor metals like gallium.

Notable in their ability to improve speed and power-handling capability are gallium-based devices like GaAs and GaN. (See S. K. Sahu, S. T. Chacko, O. Parmar, and A. S. Rajput, "Wide bandgap Materials: Revitalizing Power Electronics with Advances in Power Semiconductor Devices," *J. Inst. Eng. India Ser. B*, vol. 106, no. 4, pp. 1287–1303, Aug. 2025. Available at https://link.springer.com/article/10.1007/s40031-025-01205-4). Besides semiconductors, Ga is used in other rapidly growing optical applications, including LEDs, displays, and fiber-optic networks. (See W. G. Wong, "High-Speed Interfaces Push Optical Connectivity," *Electronic Design*, Jan. 22, 2016. Available at https://electronicdesign.com/communications/high-speed-interfaces-pushing-optical-connectivity.)

Another sometimes overlooked application of Ga is in high-efficiency rare-earth (NdFeB) magnets, where small amounts of Ga may be added to optimize performance. Because magnets are more massive than microchips and can be employed in large-scale energy-related applications like high-efficiency motors and wind-turbine generators, the ultimate Ga demand for these kinds of magnets could significantly add to the aforementioned applications.

Concerns about limited natural resources and energy, coupled with growing amounts of consumer end-of-life electronic product waste,

have given rise to regulatory requirements and voluntary initiatives to improve product sustainability. Disciplines like industrial ecology have become the basis of a total life cycle approach, where raw-material extraction, production, use, and end-of-life phase all must be considered.

Design for Environment methods for electronic and electromechanical products are also becoming standardized. While overall adoption of these best practices has been substantial, achieving life cycle maturity for Ga, in particular, has yet to be realized. As it turns out, this is not easily accomplished and remains a long-term challenge.

Next, we review the availability of Ga from naturally occurring sources and where it's used. This quickly leads us to consider elements beyond Ga itself. We then discuss how basic principles of sustainability and product stewardship could be applied to achieve an improved Ga life cycle and conclude with some prospects to improve this metal's sustainability.

Sources of Gallium

The overall availability of elements depends on several factors, including natural abundance; ores having sufficient concentration to enable economically viable extraction; commercially available processes for refining; and established flows to recycle waste. Gallium is relatively rare and is not found naturally as the metal itself. It occurs mainly as the mineral gallite, $CuGaS_2$. Although the copper (Cu) might suggest that copper would be a natural source of gallite, it is not found in significant concentrations in copper ore; instead, it is only concentrated enough for commercial extraction as a secondary product of aluminum and zinc—a relatively rare substance on its own. From a sustainability perspective, limited resources are a major concern, along with others like toxicity.

The familiar element silicon, which is highly purified for use in microchips, is comparatively unlimited as a starting material, as are common mechanical and structural metals like aluminum and iron. It's the relatively low but commercially viable concentration of gallite in

bauxite, the naturally occurring form of aluminum, which we will find contributing to the sustainability of Ga. To summarize, Ga is a limited resource and is a child metal dependent on other metals for its production.

It's worth noting that Ga is actually less abundant than some of the 17 rare-earth elements, including cerium, lanthanum, neodymium, scandium, and yttrium (not shown in the table). The rare earths deserve special mention because we refer to them later in the context of energy-critical elements and their life cycles and sustainability.

Gallium Recycling

Recycling of precious metals like silver and gold has existed for millennia due to their even more limited resource availability and highly desired qualities for a variety of monetary, jewelry, and technical applications. In other words, they are valuable (hence called precious metals). Aluminum, iron, zinc, and copper, as well as other commodity metals, are somewhat less valuable financially but nonetheless enjoy a robust infrastructure for recycling.

The main sources of recycled metals are so-called new scrap from manufacturing processes prior to being sold on the market, and old scrap from items discarded at the end of their intended use. Both sources, plus virgin ore, are then made into new metals to sustain their life cycle and make new products. In addition to helping close the loop on material reuse, significant energy savings may result when processing recycled metals as compared to virgin ore.

GaAs can be recycled internally from new scrap generated in operations like wafer processing. But neither Ga nor As has achieved commercial recycling of old scrap. Whether this is an immediate concern is discussed later in the chapter.

Much can be learned from existing success in recycling the various materials in high-volume consumer products. Separation and recycling technologies exist to improve the closed-loop resource usage of ferrous and non-ferrous metals, precious metals, and, to a lesser extent, glass, ceramics, and plastics.

While metals generally can be recycled and reprocessed virtually indefinitely into making new products, nonmetals and plastics tend to be downcycled into less-critical applications. In many regions, the major metals in high-volume consumer devices like cell phones can be dealt with in an environmentally sound manner, while rarer metals like Ga tend to end up more or less "unaccounted for" in what remains a waste fraction.

Opportunities for Ga Life Cycle Optimization

Materials flow-analysis techniques have shown that Ga is currently recycled only from new scrap in GaAs wafer manufacturing. How can Ga use become more sustainable? Solutions may require combined materials recovery, including uses of Ga beyond semiconductor chips.

Somewhat surprisingly, coal ash has been reported as a significant source of Ga. While we would not generally promote burning more coal for that purpose, existing piles of coal ash could be an interesting potential source of old Ga scrap.

Due to the energy-saving and energy-generating aspects of LEDs, photovoltaics, and rare-earth magnets, and their reliance not only on Ga but other scarce elements, focus has been brought to bear on assuring a sustainable supply of these elements. Recognition of these energy-critical elements is the first step in creating awareness and establishing policies that may help promote the sustainability of these elements as a general goal.

Product designers should strive to reduce materials use, minimize their variety in a product, and choose materials with lower environmental impact and those that are easily recycled. Unfortunately, these goals are difficult to realize, since Ga in microcircuits is actually used to replace—for performance reasons—the more abundant Si. On the positive side, minimal amounts of Ga are inherently used by design. The recycling of GaAs from new scrap (wafer manufacturing) has already been mentioned.

Merging new materials like graphene may hold promise as an alternative material, since graphene is based on very abundant carbon.

Another novel approach would substitute oxides of more common metals for those of limited supply. At this time, these are still areas for future development.

End-of-Life Product Issues

One of the means to improve recovery of any material is to ensure that it can be easily separated from other fractions to improve the purity of the recycling stream. It might be possible to use the natural grouping of GaAs-containing devices on a particular area of a cell-phone circuit board, for example, but generally the entire board is considered a recyclable fraction by itself. Though the major metals mentioned so far can be recovered by smelting and refining, that's not yet the case with trace elements like Ga. Figure 3-1 summarizes the current life cycle of Ga, showing that fully-closed-loop recovery has yet to be achieved for old scrap (i.e., end-of-life products depicted by the dashed line and "old scrap" box).

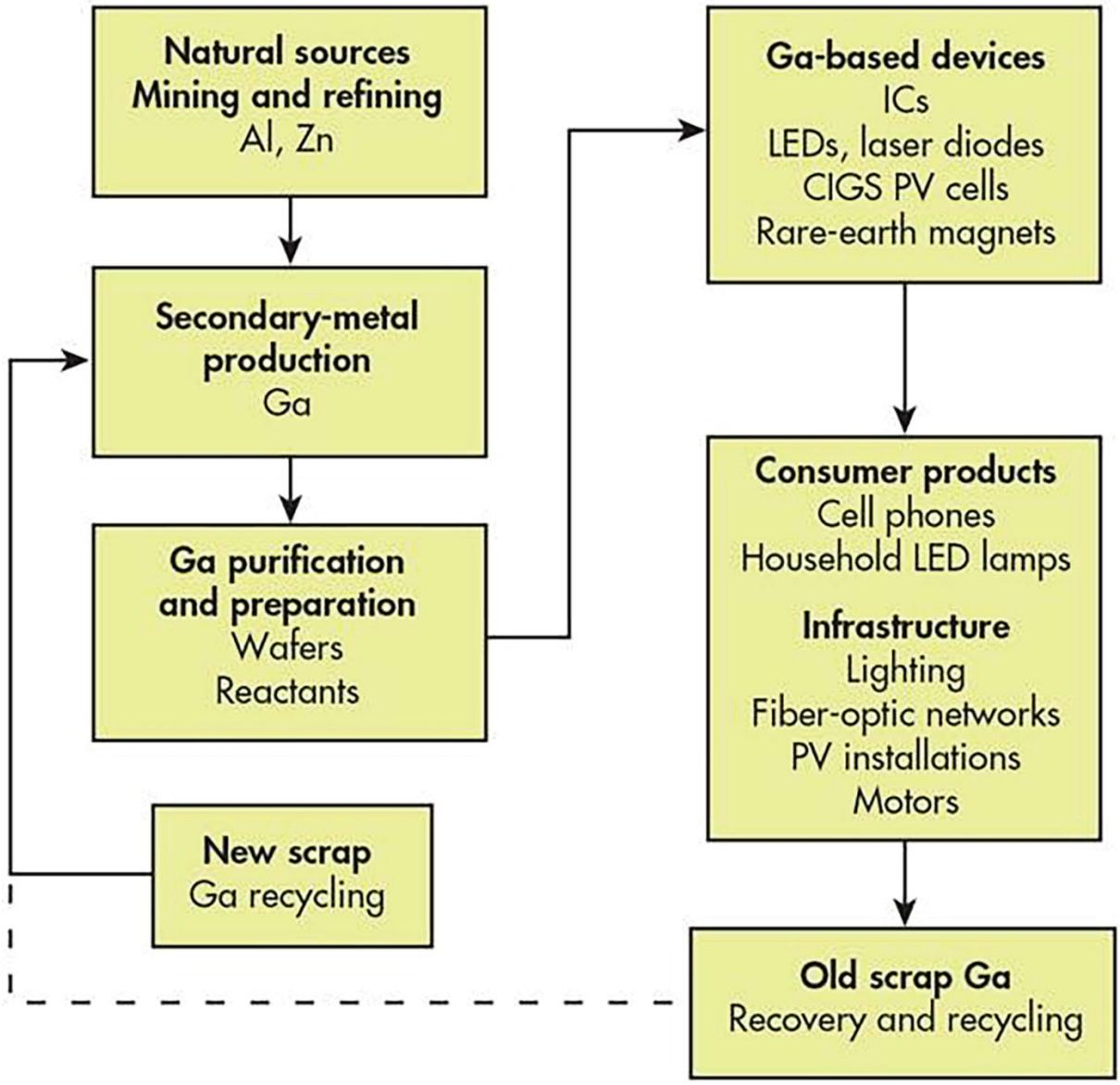


Figure 3-1 Life cycle of gallium

The gallium life cycle has yet to attain fully closed-loop recovery for end-of-life products. In fact, every element that is mined needs its own life cycle and recovery flow, which only recently has come into action. Along with so many other elements that are technologically useful, industry and other forces have yet to optimize their full life cycle for ongoing sustainability.

Does Ga need an established old scrap recycling flow of its own? The answer depends on several factors, but as of now, the availability of

primary sources, namely Al from bauxite, ensures a sufficient supply. This picture could change if demand for Ga grows significantly for current applications or new technologies.

Like any commodity, the future recovery of Ga will be driven by its concentration vs. price curve. A combined means of concentrating Ga from all end-product applications would then likely be the key to improved closed-loop recycling. Today, special collection and treatment of Ga-containing end-of-life products—PV installations, LED lighting, fiber optics, and rare-earth motors—remains to be established. Supply and demand will drive upcoming trends in this area.

Conclusion

We have summarized the available sources for Ga, its electrical and electronic applications, and the current state of closed-loop recovery. Improved recovery of Ga in the long term will depend on its demand and the ability to economically concentrate it from various sources for recycling. Presently, Ga slightly fails to reach a sufficient concentration in waste streams like mobile-phone circuit boards, PV installations, fiber-optic communications, and lighting applications, to fully close the loop. Collecting and combining Ga-containing products from several of these waste streams could change this scenario in the future.

Similar problems exist with achieving perfectly circular solutions for many other electronics materials and elements.

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More Metals and Minerals

So far, we have highlighted restricted metals, lead in particular, while providing coverage of two other electronics metals, copper and gallium. Because every material is ultimately made of chemical elements, this book could easily turn into a chemistry textbook, which is not our intent. Rather, to focus on sustainability, we summarize a few other categories of metals and the minerals from which they come, for sustainability may touch on other concerns about their global availability or specific consequences related to larger concerns like human rights.

Rare Earths

The name is not completely accurate since some of these elements are in the “rare earths” row of the periodic table. The lanthanides, to which scandium and yttrium are usually added, are not necessarily the rarest of all elements on Earth. Nor are they necessarily hazardous like lead or needed in large amounts like copper. But they are difficult to process and may be found naturally occurring with radioactive substances.

Some of these are critical to magnets—neodymium, praseodymium, dysprosium, and terbium—and are mentioned again in Chapter 7.

Energy Critical Elements

Speaking of energy, critical elements are so named because of their criticality to developing needs like electrification. Some lists include our familiar friend, copper, depending on which region or country is affected by its availability. Lithium, nickel, cobalt, platinum group metals, and graphite (a form of pure carbon) are becoming increasingly important for batteries, which is discussed in Chapter 7.

Conflict Minerals

From the initial definition of sustainability, this group of substances is mostly related to human rights issues, including child labor and endeavors like funding conflict in the region. Publicly traded US companies must track and report the origin of four such minerals, commonly known as 3TG (tin, tungsten, tantalum, and gold). Tin has already been mentioned for its use in electrical interconnects like component terminals and solder. Tantalum has occasional use in electronics for specialty devices, although it is most often found in mechanical parts like hardened drill bits. Tungsten is the key element used in tantalum electrolytic capacitors. Gold is used selectively as contact finishes for components like connectors, and as has been noted, due to its value, it is often the driver for recycling electronics. Conflict minerals require reporting by US companies to the Securities and Exchange Commission (SEC) (see www.sec.gov/resources-small-businesses/small-business-compliance-guides/conflict-minerals-disclosure) to comply with the United States' Dodd–Frank Act. As a departure from other substance regulations coming from the EU, based on substance and concentration regardless of origin, conflict minerals requires supply chain traceability, which is typically implemented by completing a standard reporting template.

Even here, the list has grown with extended minerals that include other elements in addition to 3TG: cobalt, copper, graphite, lithium, mica, and nickel. There is overlap among several of these; cobalt and copper in particular. Several of these, like lithium, also overlap with the energy critical metals. Nickel is a common plating used in components as a barrier layer between other metals. The interconnection of many aspects to consider is fundamental to highlighting the complex and interconnected problems making sustainability so difficult.

The overlap of conflict minerals and energy critical elements shows four of them in common, suggesting new approaches to make lithium, nickel, cobalt, and graphite more sustainably mined and more available for growing energy needs. Many elements used in electronics appear on multiple lists, from regulations to energy critical conflict minerals and extended minerals. (See www.responsiblemineralsinitiative.org/.)

Sustainable material selection requires a broad approach.

Silicon

You may be wondering why the element silicon, technically classified as a metalloid, which gave birth to the entire solid-state electronics technology revolution and has a region in Northern California named after it (Silicon Valley), has not even been mentioned. First of all, silicon itself is abundant, comprising some 27% of Earth's crust and is second only to oxygen in abundance, found most often as sand (silicon dioxide or silica) and minerals like quartz and mica. The naturally occurring forms are not particularly toxic except for very fine silica particles of respirable size (see https://oehha.ca.gov/proposition-65/chemicals/silica-crystalline-airborne-particles-respirable-size), which may be released by concrete or bricks in building construction and so on, but not from electronics.

But most importantly, while the devices and chips that run electronics are built on pure wafers of silicon (see www.isrispecs.org/orpheus_resource/circuitboards-

and-shredded-circuitboards-from-the-processing-of-end-of-life-electronics/), the other substances used to make the thin films that do the work are a very small part by weight, and further diluted by the packaging and terminations of a given component. The list of chemicals used in tiny amounts is quite lengthy, which is one reason the sourcing and circularity of today's electronics is a problem. We will not list all the chemicals going into semiconductor chips but note that "…500 different process chemicals are required to manufacture a single semiconductor chip" (see www.semi.org/en/blogs/semi-news/fluorinated-chemicals-are-essential-to-semiconductor-manufacturing-and-innovation). Sustainability concerns are not due to silicon itself, but rather to the problems of sustaining so many different chemicals and finding paths to recover and recycle them all.

This brings us to our next element of interest: carbon.

Carbon

Not a metal at all, carbon is the fifteenth most abundant element in Earth's crust and occurs in all living things. It is the main ingredient in limestone rocks (calcium carbonate).

Carbon dioxide in the atmosphere has become a recent concern due to Climate Change, which will not be debated here. In the standoff between the industries and political groups that say fossil fuels are great on one side, and the Intergovernmental Panel on Climate Change and its advocates on the other, we refer to the IPCC series of scholarly reports (www.ipcc.www.IGPP.ch), of which there are seven to date, and move on. (See www.electronicdesign.com/industrial-automation/article/21121514/lead-past-present-and-future.)

Carbon is best known for its reaction with an almost unlimited number of other elements and configurations and is studied as the discipline of organic chemistry. Chapter 4 discusses how its use in

nanotechnology holds promise for the desired next generation of sustainable electronics materials.

But first, some of the more concerning substances used in electronics that contain carbon deserve the spotlight. This subject lies directly within the domain of organic chemistry, which is the chemistry of carbon and its compounds.

Living Without Halogens and Phthalates: The Whys and Hows

Observing the halogen elements, fluorine, chlorine, and bromine, which are relevant to electronics, is not easy since their native state is a gas. Concern over their use in electronics has arisen from several sources, including the ability to form very toxic brominated or chlorinated dioxins and furans during incineration, and their general tendency to be persistent, bioaccumulative, or both. Most recently, concern over the "forever chemicals" called PFAS (per- and polyfluoroalkyl substances) compounds adds to the unfavorable family name of these chemical elements (see www.epa.gov/pfas).

https://pixabay.com/images/download/analogicus-the-light-bulb-7437502_1920.jpg

More restrictive regulations like those from the EU's REACH are pushing companies to produce products free from substances based on halogens and the organic chemicals called phthalates. What are the implications?

You will learn the following:

- What halogens and phthalates are from a non-chemist's perspective
- Why they are used in electronic products
- How they could be replaced by other substances

The Why and How

Electronics companies have experienced some chemical reactions in the past two decades. Many will recall the European RoHS Directive

(Restriction of Hazardous Substances), which came into force in 2006 and resulted in the need for lead-free components, solder, and manufacturing processes. Changes in electromechanical parts were affected, too, by restrictions on other heavy metals such as cadmium, mercury, and hexavalent chromium. The same directive also restricted two classes of flame retardants: PBB and PBDE (polybrominated biphenyls and polybrominated diphenyl ethers). These last two are organic compounds based on carbon, containing one of the halogen group of elements, bromine.

Jumping Through Hoops

For several decades now, substances containing halogens have come under scrutiny for various environmental and health effects. There's quite a history not only for the halogen-containing RoHS substances, but also for others containing either bromine, chlorine, or fluorine. In all fairness, many of these substances do their jobs quite well as insulators, flame retardants, refrigerants, cleaning agents, and so on.

Halogen concerns have risen outside the realm of electronics, notably the use of the chlorinated pesticide, DDT, highlighted in Rachel Carson's 1962 book *Silent Spring* (Penguin Classic, 1999). In 1999, there was an incident where polychlorinated biphenyls and the even more toxic chlorinated dioxins were found in livestock feed in Belgium.

Back to the world of electronics, in 1987, the Montreal Protocol prohibited the use of chlorofluorocarbons as cleaning agents and refrigerants. Various studies have also shown that improper incineration of discarded end-of-life electronic products could release extremely toxic dioxins to the atmosphere. Finally, the class of polychlorinated biphenyls, which were used widely in large transformers and capacitors, has been classified as one of what has notoriously become known as the "dirty dozen" persistent organic pollutants. You get the picture.

Now add to this scenario another class of substances called phthalates. These compounds are based on phthalic acid, with side chains attached that perform the function of plasticizers and softening

agents. Phthalates have been widely added to PVC (polyvinyl chloride), which is inherently rigid as found in PVC pipes, to make it flexible. PVC is a very common insulator that you most likely have around your home and office.

It should come as no surprise that many of the halogen-containing substances are classified as SVHCs.

Combined, these two categories—halogen and phthalate-related compounds—are nearly a third of the REACH SVHC list (see https://echa.europa.eu/candidate-list-table).

Today's Customer and Reporting Requirements and Tomorrow's Substance Bans

Another trend worth noting is for REACH SVHCs to be included in updates of the more restrictive RoHS regulation.

Of the nine phthalates that are REACH SVHCs, four of them are now also restricted under RoHS. The message is that finding more sustainable and less toxic alternatives is clearly on the to-do list for these four substances as a priority.

- Diisobutyl phthalate (DIBP)
- Dibutyl phthalate (DBP)
- Bis(2-ethylhexyl) phthalate (DEHP)
- Benzyl butyl phthalate (BBP)

While we will leave the science up to environmental chemists and toxicologists, and defer the regulations to the authorities, the bottom line is that companies may wish to take the initiative to move above the sea of regulations and develop halogen-free, phthalate-free products. In the remainder of this article, we provide some guidance on how to do just that. Fortunately, several standards organizations have published criteria that will help guide your work.

Standards to Guide You

While a company must be *compliant* with applicable legal requirements, an elective decision to *conform* to a voluntary industry

standard may also make sense because doing so brings a broader-based acceptance to a specific initiative (see Figure 3-2).

Document	Applicability	Br (ppm)	Cl (ppm)	F (ppm)	Total Halogen (ppm)
IEC/BS EN 61249-2-21	Printed circuit boards	<900	<900	N/A	<1500 (Br+Cl)
IPC 4101D-WAM1	Printed circuit boards	<900	<900	N/A	<1500 (Br+Cl)
JPCA-ES01-2003	Printed circuit boards	<900	<900	N/A	<1500 (Br+Cl)
JS709 (JEDEC/ECA Joint Standard)	Polymeric materials	<1000 BFR	<1000 CFR	N/A	--
UL QMFZ2	Plastics (non-Cl and non-Br)	<900	<900	N/A	<1500 (Br+Cl)
UL QMFZ2	Plastics (non-halogenated)	<900	<900	<900	<1500 (Br+Cl+F)
ICEA T-33-655	Low-smoke, halogen-free cables	Included	Included	Included	<2000 (Br+Cl+F)

Figure 3-2 Companies must be compliant with applicable legal requirements

Various terminology has come to be used by electronics manufacturers in this regard, including Halogen-Free, Non-Halogen, Non-Halogenated, Low Halogen, Zero Halogen, and Zerohal.

Yet another approach is to combine the definitions more broadly to include all applications yet separate from the types of halogen substances according to industry needs. The application-independent approach is used by component supplier TE Connectivity under the compliance specification for Low Halogen (see www.te.com/en/services/compliance-definitions.html).

Customer Requirements

Other classifications that also exceed regulatory requirements may be of interest to specific customers.

For example, some OEMs specify JS709 in the engineering requirements for purchased parts. These applications may include cable-based products where a fluorine-containing cable has the desired

properties for the application, and the fluorinated compounds aren't a concern or aren't listed as SVHC.

BFR/CFR/PVC-free products may also be specified. This category is an implied restriction of phthalates commonly used in PVC—unless the supplier offers a suitable substitute for conventional phthalates, an alternate base elastomer will probably have to be used to meet the customer's requirement.

While some attempts have been made by industry to develop alternatives to phthalates, they aren't as widely known, nor are they considered effective for their intended function. Moreover, even if phthalate replacement were to be accomplished successfully in PVC, the halogen content would still not be significantly changed due to the inherently high chlorine content of PVC (some 57% by weight). Because of these factors, current trends point to eliminating PVC as a basic material for insulation and jackets when required by the customer.

In the next sections, we discuss some of the available choices in selected commodity types—electronic components, plastics, and cables—and how they can be successfully implemented into products.

Circuit Boards and Components

Flame-retardant thermosets, including the epoxies and similar materials used for laminates, have traditionally contained halogen reacted into the polymer backbone. Device packages like discrete semiconductors, ICs, and molded passives like tantalum capacitors and encapsulated inductors have used similar materials. Only those components that are primarily made of metals and/or ceramics, such as resistors, multilayer capacitors, permanent magnets, and so on, are usually considered to be inherently halogen-free.

Traditional FR-4 epoxy circuit-board laminates have been made using a rather clever chemical reaction, where a brominated flame-retardant monomer, tetrabromobisphenol A (TBBPA), is reacted into the epoxy thermoset polymer backbone of the laminate. This loading of bromine provides significant flame-retardant properties.

Considerable work has been done by suppliers and industry groups to develop, standardize, and make available halogen-free circuit board materials (see www.pcbdirectory.com/manufacturers?pcb_type2=Halogen-free). One implementation is in the multilayer circuit board that's used in the ChipConnect cable assembly (see www.te.com/en/product-2821719-1.html). This is an internal faceplate-to-processor cable assembly running at 25 Gb/s. Variations include one or two ports, with either linear or right-angle connectors available at the linear edge-connector end.

Circuit boards can be specified to conform to the JS709 standard, with less than 1,000 ppm (parts per million) each of brominated and chlorinated flame retardants. (See https://solutions.borderstates.com/wp-content/uploads/2025/08/12730_2025_Conflict-and-Extended-Mineral-Flyer.pdf, www.ipcc.ch/, and https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14172-Hazardous-substances-exemption-for-lead-as-an-alloying-element-in-steel-aluminium-and-copper_en). These are being made in a variety of constructions and thicknesses.

Alternate solder-mask pigments that are halogen-free are also available. Typically, these have been based on the compound phthalocyanine green, chemical formula $Cu(C_{32}N_8Cl_{14})$, which isn't halogen-free. However, there's a chlorine-free alternative that's the same molecule without chlorine, shifting its color to blue, and known as phthalocyanine blue, $Cu(C_{32}H_{16}N_8)$. Solder masks are also available that are halogen-free

Following the switch to lead-free terminations, semiconductor suppliers have followed up with halogen-free mold compounds for device packaging. A quick survey of the top semiconductor companies finds all to list halogen-free molded packages, as do many other semiconductor suppliers.

The availability of low halogen products from suppliers of molded passive components like tantalum capacitors has evolved similarly. Low halogen developments are ongoing, so the best source of information is web searches and direct contact with your preferred suppliers. While space prevents further discussion here, design teams should be aware of the options and inquire about availability. Keywords found in this article may be of benefit to your search.

Plastics and Flame Retardants

Plastics often need to have flammability protection for their intended applications and be rated by safety agencies. Suppliers have been developing alternatives to classical brominated and chlorinated flame retardants, beginning even before the original RoHS ban on PBB and PBDE. Other types of non-RoHS brominated flame retardants may still be used (e.g., hexabromocyclododecane (HBCDD). However, its listing as a REACH SVHC is driving the move away from brominated compounds entirely. Some of the most promising replacement substitutes have been based on nitrogen and phosphorus.

TE MATE-N-LOCK is an example of a product line that has low halogen content. The 350766-1 plug housing, with a 3-position, 0.25-in. pitch for wire-to-board or wire-to-wire applications, is rated UL 94V-0 (see www.te.com/en/product-1-350766-1.html).

Low-Smoke, Zero Halogen (LSZH) Cables

Without chlorine, polyvinyl chloride (PVC) would not exist. Achieving viable fluorine-free jacket materials has been challenging for cost-sensitive commercial products. Removing both fluorine and chlorine leaves compounders with few options, except to pursue polyolefin or elastomer-based ingredients, including LDPE, LLDPE, TPE, and TPU materials. In addition to verifying the low halogen content, candidate replacements must pass applicable low-smoke density tests, for example, UL Standard 1685 or IEC 61034 (see www.tuc.com.tw/).

Product offerings change rapidly, so specific manufacturer offerings are not listed here. Rather, the reader may consider searching for

current needs in these product categories.

- Low Smoke Zero Halogen (LSZH)
- LSZH cables for data centers
- High reliability aerospace cables
- Marine and military qualified products
- LSZH heat-shrink tubing

For Further Reading

R. L. Franz, "Living without halogens and phthalates: The why's and how's," *Electronic Design*, Dec. 18, 2018. (https://www.electronicdesign.com/technologies/analog/article/21807404/living-without-halogens-and-phthalates-the-whys-and-hows)

What Next? PFAS

In the electronics world, until recently the focus was on substances like chlorinated and brominated flame retardants, or the polymer polyvinyl chloride (PVC). This is rapidly changing with the entry of the latest group of halogen-containing chemicals of concern: a large group called PFAS, which stands for per- and polyfluorinated alkyl substances.

While we do not intend to get deep into chemistry here, a picture of one of these substances, called perfluorooctane (built with the same basic eight-carbon octane structure found in gasoline), may be of interest (see https://pubchem.ncbi.nlm.nih.gov/image/imgsrv.fcgi?cid=9387&t=l). To the author, it looks like a zipper, but to the environment, it acts more like a slippery but very immovable boulder, since it totally violates Green Chemistry Principle #10, Design for Degradation (see https://pubchem.ncbi.nlm.nih.gov/image/imgsrv.fcgi?cid=9387&t=l).

In a simplified chemistry illustration, each junction of lines represents a carbon atom, which naturally bonds to four different

partners. Since we will spend time explaining the promise of carbon-based electronics very soon in this book, it needs to be made clear that this was not the way to go about achieving sustainability.

When we say large numbers of PFAS, the list of these substances kept by the OECD (Organization for Economic Co-operation and Development (www.oecd.org) numbers some 4,730 of these chemicals. The US Environmental Protection Agency (EPA) (https://epa.gov/) maintains similar tracking and has publicized guidance to help understand more about where these substances that are so resistant to breaking down that they have been called "forever chemicals" (see www.epa.gov/pfas/pfas). While other uses in everyday consumer products, including cookware and other non-stick applications, are most often mentioned, electronics manufacturing is noted there. Worse yet, applications we do not want, like appearance in food and water, are perhaps the greatest concern at present. As is so often the case, they do have very unique and useful properties, but unfortunately their place in a sustainable world has yet to be figured out.

As a case study of how difficult substitution is, one of the lead-containing materials that has very useful electromechanical properties is lead zirconate titanate (PZT). Current RoHS regulations allow its use with an exemption for lead in ceramics. If one wants to be proactive about reducing lead, one of the available alternatives is a lead-free polymer based on polyvinylidene fluoride (PVDF). Guess what? This substance is a PFAS, so it is not exactly a perfect replacement. More research is needed; this is a common theme here.

Future editions of a book like this will no doubt contain many pages devoted to progress addressing PFAS substances, but until worldwide regulations specific to electronics appear, this section will be kept brief. Some PFAS are also found in small amounts as additives in other engineering plastics, which is the subject of the next section of this chapter.

We have traced the trend from environmental regulations and industry standards to customer requirements for products without

halogens and phthalates. PCBs, molded components, plastic parts, cables, and shrink tubing across diverse electronics industries are all maturing to meet these needs.

The halogens and phthalates we have discussed here represent an ongoing trend where regulations become more restrictive. REACH Candidate List of substances (SVHC) can move under the more restrictive RoHS category, as witnessed by the four phthalates we have discussed. Meanwhile, environmental watch groups may also continue to pressure industry to improve the environmental performance and total life cycle management of electronics products.

Addressing the Global Plastics Problem in Electrotechnical Product Design

Introduction: Plastics Everywhere

More than just unsightly "plastic pollution," the volume of consumer plastics and lack of closed-loop recovery have created a significant microplastics and nanoplastics problem. These invisible plastic particles are found around the world, including in animal and human tissues.

https://pixabay.com/images/download/thedigitalartist-ai-generated-8286573_1920.jpg

For several reasons, including a much smaller volume of plastic used in electrotechnical products compared to consumer plastics and the generally longer life of hardware compared to the rapid turnover of consumer goods and packaging, the microplastics problem is not typically tagged as a major electronics problem—or at least not yet. *Now is the time to be proactive.*

The United Nations Environment Programme (see https://one.oecd.org/document/ENV/JM/MONO(2018)7/en/pdf) has posted summaries of recent discussions on using the Life Cycle Assessment (LCA) to address the global problem of plastic pollution. These Life Cycle Initiative areas relate to plastic products,

chemicals of concern in plastic products, and plastic product design. The documents are about possible approaches to managing plastics with recommendations but are not detailed prescriptions, methods, or regulations.

While the studies did not specifically mention electrotechnical products, this industry will need to accelerate focus on engineering design tools and engineering plastics choices to avoid significantly adding to the consumer plastic product problems.

Within the UNEP product design discussion, the section on "General considerations on possible approaches to product design, focusing on recyclability and reusability" included the following important point, which bears repeating: Product design approaches should include eco-design and circularity principles.

Product Design Approaches Should Include Eco-Design and Circularity Principles

But what does this mean? In the following discussion, we hope to break these approaches down into more tangible design choices. Even within the electrotechnical product category, there are many product variations, so no claim is made here to cover all of them.

Options for lower carbon footprint plastics already exist to some extent. Except for packaging, electronic components and products are typically made with engineering resins rather than the common consumer plastic "recycling arrow" types. Alternative types of lower carbon footprint engineering resins may be available to use rather than others with higher carbon footprints.

Many plastic manufacturers are currently conducting LCA to quantify the cradle-to-gate carbon footprint of their materials. Different polymer types have inherent differences in carbon footprint due to their different monomeric starting materials and manufacturing processes.

For many plastics, these flows are detailed by europe.org. Polycarbonate, ABS, and several polyamides, for example, are included. What is missing in these publicly available sources, as well as LCA

inventory databases themselves, are many other engineering plastics; for example, while consumer PET is widely modeled, PBT (polybutylene terephthalate) is not. These are just some of the data gaps that need to be resolved.

More sustainable feedstock is a good option since a given end polymer may be made from different monomeric chemicals, so the more sustainable plastic performs exactly like its classic version because it is the same. One of the growing alternatives includes feedstocks based on renewable, bio-based sources.

These need some evaluation, again using LCA, to ensure they are free of downsides like increased water use, eutrophication, and chemical pollution due to the use of herbicides, pesticides, fertilizers, and so on. Marketing claims of being a "green material" will need backup data (see www.epa.gov/pfas). An earlier draft of this book included a reference to the very useful and practical FTC Green Guides. However, at this time, the FTC guides are no longer available due to a lack of US government funding. Economic priorities need to address this short-sighted lapse when possible.

Reducing the amount of plastic by design is not only a good practice for sustainability; it also saves money. Some designs using parts with enough material to be modeled using generative design may be able to reduce the amount of material while reducing material usage and weight. Reducing factory scrap from injection molding processes, leaving sprues in runners, and using captive regrind are other good options.

Choosing manufacturers using renewable fuels—and even benefits like reduced water use during processing—is another area of choice for sustainability. Local sourcing is also a way to reduce the overall carbon footprint of a material by reducing the contribution of transportation.

Identify large plastic parts: historical guidelines on eco-design have actually been around for years. One good early example was the ECMA 341 Standard, "Environmental Design Considerations for ICT & CE Products" (4th Edition, December 2010), which says, "All plastic parts weighing 25 g or more and with a flat area of 200 mm2 or more are

marked with the type of polymer, copolymer, polymer blends or alloys in conformance with ISO 11469." (See www.ecma-international.org/wp-content/uploads/ECMA-341_4th_edition_december_2010.pdf.) This practice enables the identification of plastic types of large parts, while in practice, the ability to sort becomes less useful when a variety of goods are mixed in a production recycling facility. Success here depends on either manual sorting or more sophisticated methods like infrared spectroscopy to be effective. Some equipment recyclers have such capability.

Keep it clean: More useful guidance from ECMA 341 is to *avoid* the following: non-recyclable composites; coatings and surface finishes on plastic parts; adhesive-backed stickers or foams on plastic parts; if stickers are required, they should be separable; and metal inserts in plastic parts unless easily removable with common tools. These are common sense from a clean recycling stream perspective and should not be difficult to implement.

Closing the end-of-life loop: Recycling is imperfect, and as far as this author has seen, it is rarely in place for engineering plastics.

Processes under development to decompose plastics back to new monomer feedstocks are called chemical recycling (see https://worldplasticscouncil.org/resource/chemical-recycling-plastics-circular-economy/). This approach is achieving some success with a limited number of materials, mostly for high-volume consumer plastics rather than engineering types.

A biochemical research paper by M. Dashtban et al. titled "Fungal biodegradation and enzymatic modification of lignin" (see Int. J. Biochem. Mol. Biol., vol. 1, no. 1, pp. 36–50, May 2010. Available at https://pmc.ncbi.nlm.nih.gov/articles/PMC3180040/) explains how it works, for example.

A similar approach to chemical recycling was reported by T. Thiounn and R. C. Smith in "Advances and approaches for chemical recycling of plastic waste." (See *J. Polymer Science*, April 20, 2020. Available at

https://onlinelibrary.wiley.com/doi/full/10.1002/pol.20190261.)

LCA is needed to validate that achieving plastic circularity this way, with the necessary processing energy and chemicals, will have a net environmental benefit. The obvious problem with all approaches is that plastics were never designed for the environment in the first place.

Selecting more sustainable additives is another area where product engineers have some choices. There are thousands of possible additives used in plastic, usually specified for a given grade and end application. These include flame retardants, processing aids, fillers, colorants, ultraviolet stabilizers, plasticizers for flexibility, and so on. While these choices are primarily the responsibility of the resin manufacturer, pressure from regulators and industry demand can influence the use of more sustainable additives.

Whenever possible, new products should avoid regulated substances by design, which may include SVHCs as defined by the European Chemicals Agency (ECHA) and, more recently, polyfluorinated substances called PFAS. This is easier said than done but definitely belongs to the checklist of eco-design considerations.

Other options are being developed to improve the sustainability of plastics; here we have in mind specifically the specialty plastic used for engineering purposes, although similar principles apply to high-volume consumer plastics like those used in packaging. We consider two ends of the plastics problem.

- **Supply side**: Studies generally show that reducing the amount of plastic used in the first place helps improve sustainability. (We take this up again in Chapter 6.) A developing alternative for some materials is the use of renewable bio-based feedstocks. Such polymers may then be made with the same formation and properties as those made of fossil fuel-based raw materials. As with most such trade-offs, bio-based sources must not compete with food sources, cause major land use changes, water depletion, and so on. Only full-range LCAs can adequately address all of these. Some hybrid

approaches are also being seen where some of the feedstocks are bio-based, and the rest remain fossil fuel in origin.

- **End-of-life side**: Plastics tend not to naturally degrade in the environment. Changes to polymer design to improve biodegradability are being seen, as well as others specifically designed with a kind of key to unzip the polymer into smaller fragments that can be more easily handled naturally. More examples of recyclable polymers are covered in Chapter 5.

Meanwhile, are there other choices besides plastics? Using different materials altogether may be possible in some cases.

High-volume hardware is probably unable in many cases to use alternative materials like wood, glass, bamboo, and so on. Historically, though, until the rise of both solid-state and plastic technology in the 1950s, radios and televisions featured wooden cases and consoles. Miniaturization in the solid-state era brought in mostly plastic housings.

One recent example of a different approach that the author worked on was an audio teleconferencing system (see www.ftc.gov/news-events/topics/truth-advertising/green-guides) that featured either oak or walnut product housing to blend with the executive conference room (see https://content-files.shure.com/KnowledgeBaseFiles/AL772C-ST3000.pdf?term="Dashtban M"%5BAuthor%5D). While the intent was not specifically to avoid using plastic, it is an interesting example of thinking outside the plastic box. Wood avoids many of the issues with plastics, but of course, the other plastics like PCB's and component packages in the circuitry remain to be addressed. Like all other natural resources, wood can also be misused.

A few words about wood: What is old may be new.

> "Wood is the fifth most important product of the world trade. Vast quantities of wood are logged by foresters to provide fuel, fibers (for pulp, paper products, and boards), and sawn timber

(for house building and furniture) as commodities. The complex chemical makeup of wood (cellulose, hemicelluloses, lignin, and pectins) also makes it an ideal raw material for what could be a future "ligno-chemical" industry that could replace the petrochemical industry, in providing not only plastic and all kinds of chemical products, but also food and textile products." (See C. Plomion, G. Leprovost, and A. Stokes, "Wood formation in trees," *Plant Physiol.*, vol. 127, no. 4, pp. 1513–1523, Dec. 2001, doi: 10.1104/pp.010816).

End-of-life electronics could use something like naturally occurring white wood rot fungus that recycles complex polymers in plants back to raw materials in an endless cycle. This occurs in wood—and, honestly, the complex polymers in wood do not easily just "fall apart" either!

Lignin, the most abundant aromatic biopolymer on Earth, is extremely recalcitrant to degradation. (See https://content-files.shure.com/KnowledgeBaseFiles/AL772C-ST3000.pdf?term=) One of the many emerging material technologies is engineered wood. The research hardly suggests that a wood-based material could be a drop-in, for example, to replace injection-molded thermoplastics, but the possibility is most intriguing. Just having a material of natural origin is not automatically a panacea for replacing plastics, but it could be more promising than more plastics. (See Y. Mao, L. Hu, and Z. J. Ren, "Engineered wood for a sustainable future," Matter, vol. 5, no. 5, pp. 1326–1329, May 2022. Available at www.cell.com/matter/fulltext/S2590-2385(22)00165-5.)

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https://onlinelibrary.wiley.com/doi/full/10.1002/pol.20190261e. One can still find toys made of wood.

Only LCA can quantify the trade-offs between material choices.

For now, the point is that reconsidering classical synthetic polymers in the light of more natural and renewable materials may have an interesting future.

Modularity

The ease of disassembly into "modules" is often listed as an eco-design practice that improves circularity, but the present author is skeptical about providing practical details. More specific guidance requires each manufacturer to know how its products can be disassembled at their end of life and where such disassembly would lead in terms of reuse, remanufacturing, or material recovery. In the context of plastics, a large plastic housing that can be easily disassembled into a single clean material is more likely to be sent to a recycler rather than reused as a "module" in other products.

It is unfortunate that software tools to make early design choices for disassembly began to be developed 25 years ago but have gone by the wayside since. The author had personal experience with such a "Green Design Advisor" tool that modeled a product assembly from its raw materials and showed how disassembly into environmentally and economically viable recovery fractions could be optimized.

One example that is probably still true today is that an epoxy circuit board and its components would be a "module" to be submitted to size a reduction, separation, and metal recovery process. Such a tool could also model the choice of a plastic housing vs. a metal alloy and the impacts of circular recovery of the material choices. Disassembly modeling tools for product designers are an area that needs significant development now, while software using artificial intelligence (AI) claims to be the answer. We shall see.

In conclusion, it must be recognized that most plastics were never designed for the environment in the first place. While there is currently no 100% perfect alternative, engineers do have options to improve the life cycle sustainability of tomorrow's products.

Summary on Plastics

- Select lower PCF plastics and avoid regulated additives.
- Reduce the number of plastics if possible and keep larger parts free of different materials.
- Consider materials other than plastics.

- Be aware of new developments in both sources of plastic and end-of-life options.
- Will cabinets made of wood ever come back? Engineered wood products might be an alternative material to fossil-fuel-based plastics.

Key Takeaways

A given substance currently used to make electronics may be at the time hazardous under some conditions, yet very useful for one or more aspects of product performance and reliability. Others, while not being particularly toxic on their own, may accumulate in the environment or may cause strain in resources due to limited availability and continually increasing demand. Legacy electronics products were generally not developed with these considerations in mind. While an encyclopedia of all the chemical substances that have been and will be used in electronics is not feasible in this book, representative examples covered here have included the metals lead, copper, and gallium, and other compounds based on carbon, like plastics that may include other chemicals, or the sheer volume of plastics, especially the engineering types, that so far are in need of a better closed-loop life cycle. The next chapter begins to propose some improved options.

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R. L. Franz, *Closing the Circuit to Sustainability*, Maker Innovations Series
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4. Sustainable Materials

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This chapter begins to reveal some possible ways to improve upon the unsustainably complex set of chemical elements and materials used to make not only classical components but also the latest devices in electronics technology. A possible better way is aligned with one of the four ecological principles introduced in Chapter 1.

What you will take away from this chapter

- How carbon could be used to make more sustainable products
- Introduction to nanotechnology
- Components based on carbon nanotechnology
- Carbon and flexible electronics
- How chemical complexity and toxicity can be reduced

The Future of Carbon Electronics

The main building block discussed here, the element carbon, is not the only possible solution to build tomorrow's more sustainable hardware, nor will it likely be used all by itself. But it does provide a common theme around which a most compelling story about the new, specialized kinds of carbon that are being demonstrated to be viable building blocks for tomorrow's more sustainable hardware.

What you will learn in this section

- Why is carbon of interest for future electronics?
- What kind of carbon will it be?
- Where will new applications using carbon be found?
- How can carbon electronics be successful and sustainable?

Why Carbon?

- More than half of the naturally occurring elements are used in today's electronics.
- This complex demand could be simplified by using carbon.
- Reliance on toxic or critical elements could be reduced.
- Carbon is an abundant starting material and can be recovered or recycled.
- Full life cycle considerations can be made an important part of carbon R&D.

This is about the solid element carbon, not carbon dioxide gas that is implicated in climate change.

Carbon is not new to electronics. Resistors based on various forms of carbon, from bulk composition type to carbon films, have been used in electronics for decades. What is new is the promise of carbon nanotechnology.

Carbon composition and carbon film resistors are familiar components. Carbon is a weak conductor, and although not technically a semiconductor as we know those materials today, it can make a good resistor.

When combined with other elements to make polymers, it becomes a very good insulator, like a resistor body. Combined with other carbon-based materials already used for component packages, substrates, wire insulation, and so on, carbon compounds (called *organic*) are in all kinds of products and, of course, life itself.

But it was the recently discovered forms of carbon that sparked new interest. This exciting material technology is introduced next.

Enter Nanomaterials

The 1996 Nobel Prize in Chemistry was awarded to R. F. Curl, H. W. Kroto and R. E. Smalley for their work on *fullerenes* made entirely of carbon (see www.nobelprize.org/prizes/uncategorized/the-nobel-prize-in-chemistry-1996/).

- 1 nanometer = 10^{-9} m (1 trillionth)
- Nanomaterials are in the 1 to 100 nm range
- For reference, the width of a human hair, by comparison, is quite large—in the range of approximately 100,000 nanometers

It was visionary R. Buckminster Fuller (1885–1993) who designed geodesic dome structures similar to C60 (60 carbon atoms joined together). "Buckminsterfullerene" became known as *fullerenes* or *buckyballs.*

These molecules had also been identified in outer space, so the name "fullerenes" existed for some time before being synthesized and characterized here on Earth by the 1996 Nobel Prize winners.

Here we list several of the versatile forms of carbon. Some are nanomaterials, some are not.

Just the variety of carbon structures, excluding combinations with any other elements, which is the subject of organic chemistry, suggests that carbon is promising as a basic material beyond its use in resistors.

These familiar forms are *not* nanomaterials.

- Diamond, the precious stone
- Graphite, like pencil "lead"
- Regular "amorphous" carbon

These are nanomaterials:

- Buckyballs (fullerenes)
- Nanotubules (nanotubes)
- Graphene

Carbon Nanomaterial Applications

The growth of interest in carbon technology in just a few recent years is astounding.

Microelectronics soon adopted nanoelectronics. Early research on CNT FETs (field-effect transistors), for example, resulted in papers like "Carbon-based electronics: fundamentals and device applications." (R. J. Nicholas, A. Mainwood, and L. Eaves,. *Phil. Trans. Royal Soc A*, Nov. 19, 2007).

Research at the National Institute of Standards and Technology (NIST) has highlighted multiple applications of nanomaterials not only in electronics but also in related needs for energy conversion and thermal management. (Tewary, Vinod K., and E. J. Garboczi. Applied Chemicals and Materials Division, National Institute of Standards and Technology (NIST), Boulder, CO. *Modeling, Characterization, and Production of Nanomaterials: Electronics, Photonics, and Energy Applications, Second Edition* (Elsevier Ltd., 2023)).

The pace of progress is quite astounding. The pace of progress is quite astounding. The trend in the appearance of the keyword "Carbon Transistors," as measured by literature citations and patents at Google Scholar, shows an increase in the decade from 2000 to 2010 from about 100,000 to nearly 200,000 in the decade 2010 to 2020. This trend continues in the developing interest in carbon nanotechnology for electronics.

While much of the nanocarbon research is promising, the ability to be both a conductor like metal and a semiconductor in a single material is noteworthy. By wrapping a carbon nanotube with a ribbon-like polymer, the structure "…can conduct electricity, but only when the right amount of external energy is applied." (See "Engineering Carbon-Based Semiconductors for Nex-Gen Electronics," *Tech Briefs*, vol. 49, no. 3, p. 25, Mar. 2025.)

A more general review by the National Institutes of Health (NIH) (www.ncbi.nlm.nih.gov/pmc/articles/PMC6523075/) reported that carbon-based materials, including graphene, single-walled carbon nanotubes (SWCNTs), and multi-walled carbon nanotubes (MWCNTs), are very promising materials for developing future-generation electronic devices. Their efficient physical, chemical, and electrical properties, such as high conductivity, efficient thermal and electrochemical stability, and high specific surface area, enable them to fulfill the requirements of modern electronic industries.

- Energy storage: batteries and supercapacitors
- Self-powered automatic sensing devices
  - biosensors
  - gas sensors
  - pressure sensors
- Molecular electronics
- Multifunctional, wearable electronic devices and systems

Chapter 3 discussed the importance of copper as an electrical conductor. More conductive than silver and stronger than stainless steel, carbon nanotubes are one of the many reasons materials science became interested in them. Not to be overlooked is the excellent conductivity of CNTs. Given their light weight compared to metals like copper, using them for wires and cable applications has shown promise, especially for applications like aerospace and satellites where performance and weight are critical factors.

Due to cost considerations primarily, the level of interest just for wires has since declined. But there is much more to the story beyond wires. The next section on graphene will show examples of next-generation electronic components using this technology.

Enter Graphene

Graphene, an even more interesting carbon material, received attention when the 2010 Nobel Prize in Physics was awarded to Andre Geim and Konstantin Novoselov (see https://spectrum.ieee.org/2010-nobel-prize-goes-to-graphene-duo). Graphene sheets are one carbon atom thick, making them so thin they are commonly classified as two-dimensional.

The International Roadmap for Devices and Systems (https://irds.ieee.org/editions/2020), compiled by the Institute of Electrical and Electronics Engineers (IEEE), has said the following about nanocarbon materials:

> "Among emerging logic devices, "carbon nanomaterial device" (mainly carbon nanotube FET), tunnel FET, and nanowire FET were ranked as one of the most promising emerging logic devices" and "Graphene can offer possibilities for employing novel switching mechanisms for future electronics."

Switching is at the heart of digital electronics today and is expected to continue well into the future. And since silicon technology is being stretched thin (pun intended), new ways of continually increasing performance are key to the future of electronics.

The International Roadmap for Devices and Systems (IRDS) (see https://../01_Chapter%20Submission/irds.ieee.org) lists two diverging trends:

- More "Moore," that is, shrinking of existing device geometry and its variations like 3D stacking, to take us beyond Moore's law (see https://potomacinstitute.org/steps/issues/the-death-of-moore-s-law)
- Beyond CMOS, which includes
  - Emerging architectures
  - Emerging devices and processes
  - Emerging materials

Notably, in 121 pages of the IRDS, the word "graphene" appears more than 150 times.

The integration of silicon and graphene in a transistor, or GFET, was reported in detail, for example, by B. V. Krsihna et al. in "Recent developments in graphene based field effect transistors" (*Materials Today: Proceedings*, September 21, 2020; see https://pmc.ncbi.nlm.nih.gov/articles/PMC7505095).

Here's a quote from the authors of this paper:

> "Complying with the Moore's law, to increase the transistor density of an Integrated Circuit, new alternate materials for fabrication have been tried, instead of silicon due to its limitations in reducing transistor dimensions. Graphene, one such material, proves to be a suitable alternate for silicon … GFET is becoming the most suitable choice for high-speed analog VLSI, RF, and bio-sensor circuits."

This G-FET device is still made with silicon and silicon dioxide. These materials are not especially a problem from an availability or toxicity perspective. New-generation sustainable materials may still contain such now-classic materials.

Beyond building individual graphene transistors, integrated circuits are the next logical step and are made up of many individual transistors. It did not take long for that to be demonstrated. In 2011, the *IEEE Spectrum* (https://spectrum.ieee.org/first-graphene-integrated-circuit) reported the first graphene integrated circuit:

- "Although there is still a lot of work to be done to improve the device and circuit performance, it represents an important step forward to useful circuits. "
- "It will be several years before graphene devices are ready to displace conventional silicon circuits, which are expected to start hitting their limits later this decade."

Memory chips are an important part of the computer age, and carbon nanotechnology can be used there too. Some new material options for graphene memory (see https://spectrum.ieee.org/vanderwaals-heterostructure-flash-memory-5000-times-speedier) may include the following:

- Indium selenide semiconducting layer, a hexagonal boron nitride insulating layer, and multiple electrically conductive graphene layers sitting on top of a wafer of silicon dioxide and silicon.
- Molybdenum disulfide, hexagonal boron nitride, and multi-layer graphene.

These new devices are not proposed to be solely carbon-based. But the growing use of natural elements like carbon is a good trend from a sustainability perspective.

Like any modern technology, there are problems. Semiconductors like silicon and germanium have a useful band gap, an energy level between the electrons used for chemical bonding and those free to move as conductors. Typically, these materials are doped with tiny amounts of donors or acceptors to fine-tune the properties. Graphene, made of a single element, carbon, inherently lacks a band gap. Nonetheless, these are some early investigations of viable solutions:

- "Samsung Creates a Graphene Transistor with a Band Gap and Electron Mobility," by D. Johnson in *IEEE Spectrum*, May 18, 2012 (see https://spectrum.ieee.org/samsung-creates-a-graphene-transistor-with-a-band-gap-and-electron-mobility)
- "Graphene Is Grown with the Same Bandgap as Silicon," by D. Johnson in *IEEE Spectrum*, April 16, 2018 (see https://spectrum.ieee.org/grapehene-is-grown-with-the-same-band-gap-as-silicon-as-silicon)

One more interesting capability of graphene is that two layers can be twisted, changing its electrical characteristics from conductor to insulator. This has been called "magic angle" graphene, also known as Twistronics (see https://advancedcarbonscouncil.org/blogpost/2151389/516550/Physicists-win-prize-for-discovery-of-magic-angle-that-generates-supermaterials).

While the twist behavior was validated at the nanomaterial level, one may speculate that this fundamental capability of a single material made of carbon could someday help resolve the dual nature of

conductors being made of metals, and insulators made of non-metals. (Some of this duality resolution is already seen in research and applications of conductive polymers.)

More traditional materials, called Mott materials, have been called "unsuccessful metals" because they have the correct electron structure to conduct like metals, but they do not. (See A. Milloch, M. Fabrizio, and C. Giannetti, "Mott materials: unsuccessful metals with a bright future," *npj Spintronics*, vol. 2, no. 1, Art. no. 49, Oct. 2024. Also available at https://rdcu.be/fi7m3.)

The promise of twisted graphene could be significant, but it is too early to tell with certainty.

Many more graphene applications in electronics are discussed in a dedicated chapter in the advanced reference book *Sustainable Electronics* by F. Ana et al., Eds. (CRC Press, 2025).

Flexible Electronics

Circuit boards of several types have been the backbone of solid-state electronics for years. Printable and flexible electronics are now entering the picture, extending beyond semiconductors to other components required in a circuit.

> "Printed electronics technology is enabling both conductive materials such as copper and silver as well as emerging materials like graphene and organic semiconductors to be printed directly onto flexible circuits on a wide variety of substrates…. it is now already possible to print more advanced components—such as capacitors, transistors, antennae, and batteries—all on the same flexible substrate as traditional electronics."

This technology will—and already is—enabling products that are thin, lightweight, flexible, stretchable, and wearable.

Not surprisingly, the trend for flexible carbon electronics is also picking up momentum.

Keywords "flexible carbon electronics" are also taking off in frequency of occurrence.

Graphene Can Be Sustainable

This is not about replacing all of the currently used materials with carbon, but less material means less environmental impact, other factors being equal (see https://spectrum.ieee.org/vanderwaals-heterostructure-flash-memory-5000-times-speedier).

Nanocarbon devices can be put into conventional packages and assembled using existing board manufacturing processes. In the coming years, carbon nanomaterials will also help enable printed and flexible electronics, which will require manufacturing processes other than circuit board assembly.

Most importantly, graphene is made of carbon, not rare or critical elements.

One process to make graphene literally uses waste material. It has been called "Graphene Made in a Flash From Trash" (see https://spectrum.ieee.org/graphene-flash). Flash Joule heating uses a capacitor bank to apply high-voltage electricity to carbon, then heats it to more than 2,725 degrees Celsius in less than 100 milliseconds. This method produces high-quality graphene low in defects. It requires no furnace, solvents, reactive gases, or purification steps and generates little excess heat, with nearly all of its energy channeled into its target.

Besides being sustainable, such manufacturing techniques for graphene could drive costs down considerably.

Notable scientists like Prof. James Tour (see https://profiles.rice.edu/faculty/james-tour) at Rice University have made compelling calls for awareness of graphene, including testimony presented to the US Congress.

A little bit of carbon is entering a big new life. Organizations are behind the development and commercialization of graphene too.

- Graphene-Flagship.eu

  "The Graphene Flagship is part of the European Union's biggest scientific research initiative. With a budget of €1 billion, the project represents a new form of joint, coordinated research initiative on an unprecedented scale."

- https://www.advancedcarbonscouncil.com/market-reports/graphene (thegraphenecouncil.org) has recently been renamed the Advanced Carbons Council.

  The Graphene Council was founded in 2013 with a mission to serve the global community of graphene professionals. Today, it is the largest community in the world for graphene researchers, academics, producers, developers, investors, nanotechnologists, regulatory agencies, research institutes, material science specialists, and even the public. We reach more than 50,000 people with an interest in this amazing material."
- Nano.gov (National Nanotechnology Initiative)

  "…working together toward the shared vision of "a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society."

Health Effects

This book contains much discussion about toxic substances that, in fairness, were likely designed before concerns for mass distribution around Earth were even recognized. We should not repeat these oversights now with a new generation of sustainable electronics.

The US Environmental Protection Agency (EPA) is working collaboratively with stakeholders both domestically and internationally to address nanoscale materials and their research needs, and to develop international standards for nanotechnology (see www.epa.gov/reviewing-new-chemicals-under-toxic-substances-control-act-tsca/control-nanoscale-materials-under).

In the European Union, nanomaterials are covered by the same rigorous regulatory framework that ensures the safe use of all chemicals and mixtures (i.e., the REACH and CLP regulations; see https://euon.echa.europa.eu/regulation). This means that hazardous properties of nanoforms of substances have to be assessed and their safe use needs to be ensured.

Carbon nanomaterial development must be proactive to understand and address environmental, health, safety, and life cycle aspects to ensure reactive regulations do not enter into force later. Now is the time to get it right—the first time.

The Future of Carbon Electronics Is Bright

Products made with commonly available elements like carbon may help solve many of the environmental impacts associated with today's technology. With innovative technologies, new possibilities also come, like flexible and printed electronics. Reduction of hazardous substances should also be achievable if the inherent size of nanoparticles is properly understood and managed.

Progress toward making commercial carbon devices

Here we summarize some of the work underway to use carbon nanotechnology as replacements for complex silicon-based devices, under three main categories.

1. Carbon Nanotube Transistors

   Most of the emphasis has been around the workhorse of digital electronics, the field effect transistor (F FETs (CNTFETs). The ability of CNTs to improve the mobility of electrons, be more energy efficient, and rur inherently small size—as nanomaterials, they are easily made at the nanometer scale (one billionth of a me stacking devices in layers to produce 3D transistors.
2. Graphene Transistors

   Not far behind are graphene transistors (GFETs). In addition to the advantages of CNTFETs, the single-l enable flexible devices that would be compatible with trends in wearable devices and conductive textiles (s inherently has no band gap, unlike CNTFETs, a GFET without modification does not enter a completely off s approaches:

   - Stacking two layers of graphene. Remember, these structures are only one carbon atom thick, such that v optimal twist can optimize the bandgap for the device being developed. More recent research has shown with the proper twist that the highly conductive structure turns into an insulator: all with one basic carb
   - Starting with graphene oxide (remember oxygen is very abundant around us), a structure which in its na modified to work "backward" to create a smaller bandgap that behaves like a semiconductor like silicon

https://pubs.aip.org/aip/apl/article-abstract/102/13/133108/124898/Grapher graphene-based?redirectedFrom=fulltext).

3. Carbon Nanotube Integrated Circuits

Integration of multiple transistor CNTFETs is a next logical step to challenge silicon technology. Logic a technology, are not yet ready to challenge the commercial success of silicon integration or replace its exper Still, for our purposes here to propose new sustainable materials for electronics, "...nanotube carbon nanot the application of carbon-based electronics in the post-Moore era and provide a new path for the developn (see www.researchgate.net/publication/397770713_Research_Progress_of_Carbon_Nano

For Further Reading

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H. Li, J. Zhang, L. Wang, and Y. Liu, "High-performance carbon nanotube electronic devices: Progress and challenges," *Nanomaterials*, vol. 15, no. 5, p. 642, Mar. 2025.

Additional Perspectives on Carbon-Based Components for Sustainability

This section expands on the use of carbon to make devices like transistors and memory chips and consider how next-generation materials may help improve sustainability and circular material cycles (see https://technology.nasa.gov/t2media/tops/tn/TOP2-111/ARC_15460_1_Front_image.jpg and https://contenthub.llnl.gov/sites/contenthub/files/styles/orig/public/news/2010-10/15701_membraneBig.jpg?itok=VP4tI972 type=).

With the exception of the memristor, which is covered in Chapter 7, the basic passive and active circuit elements that operate on basic electronic attributes like voltage, current, resistance, capacitance, and inductance will likely function largely as they do today even when they are built from next-generation materials.

What you will learn in this section

- Current directives and standards targeting end-of-life recycling
- How carbon nanotubes are being used to rethink how components are made with fewer chemical elements
- The latest advances in graphene-based developments

This story of future electronic component materials may benefit from some perspective on the distant past. Consider the Stone Age that lasted for millions of years, when humanity was limited to tools made of, well, stone. Just a few thousand years ago, the Bronze Age brought in metalworking using copper and tin. What followed in the more modern Iron Age was iron alloyed with carbon to make steel. These phases of early technology have a short bill of materials.

Fast forward to today, where microelectronics is based on complex thin films that are typically, but not exclusively, on silicon substrates. These devices may incorporate dozens of chemical elements and many

more chemical compounds. One such list that covers just semiconductor materials, compound materials, and alloys made of between one and four chemical elements numbers over 100. The necessary peripheral components like passives and interconnects add even more.

Packaging of final products is also interesting, but that will be saved for another time. It does, however, offer a return path for common metals that will be needed only in lesser amounts for carbon-based devices and could be recovered in the same recycling processes, as discussed further in Chapter 5.

Advances in End-of-Life Recycling Tech

The electronics end-of-life recycling technology is becoming established for some metals at least, and to a lesser extent with larger plastic parts used as device housings. Thanks to requirements like the EU's WEEE Directive on Waste Electrical and Electronic Equipment (see https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en) and similar regulations in US states, infrastructure is developing for recovery and recycling of electronics.

The issue is that, except for a few common metals, notably copper and precious metals like gold, palladium, and silver, almost nothing else from components is recovered to go back to its next life. In the European Union, standard "EN 50625-Part 5: Specification for the final treatment of WEEE fractions—Copper and precious metals" (see https://standards.globalspec.com/std/10178081/ds-clc-ts-50625-5) requires at least 90% recovery by mass of copper, gold, silver, and palladium. These kinds of requirements help ensure that at least these important metals will have a recovery stream in some regions.

Sustainability and carbon footprint are big topics these days, and the electronics industry is quickly becoming a significant enabler of the low-carbon economy. But from a materials perspective, while devices and products continue to get physically smaller and include more software content, the number of specialty materials continues to grow (see www.isri.org/recycled-commodities/isri-specifications-circular).

Here we speculate how electronic component technology might continue to evolve while realizing some rollback of the growing number of Earth's resources that are required. Figure 4-1 shows how a less-resource-intensive and more-closed-loop product life cycle could be accomplished by using nanotechnology based on specific kinds of the common element, carbon. In order, clockwise from top left:

1. Earth provides the basic resources.
2. Resources are purified and modified, traditionally with little regard to the next steps.
3. Products enter the use phase in the marketplace. When sustainability is applied, the lifespan may be lengthened, reducing the demand on step 1.
4. This step needs to evolve from garbage to efficient reuse of resources from step 1.

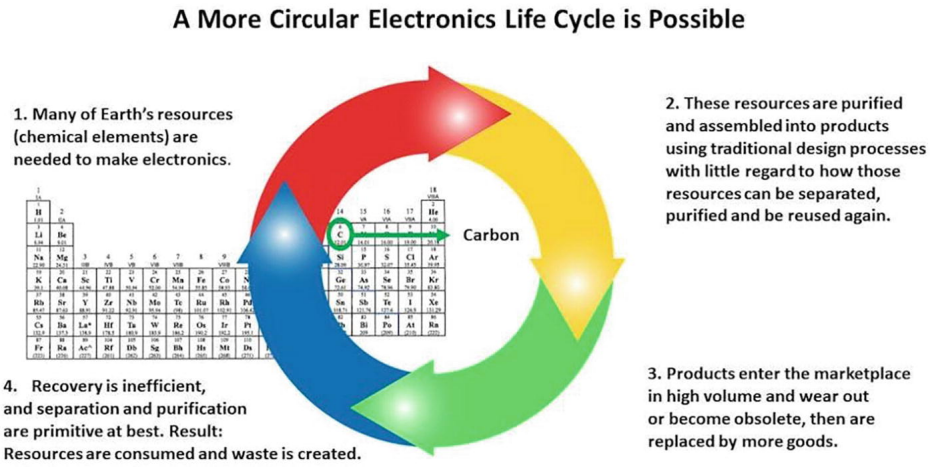


Figure 4-1 Four aspects of improving the product life cycle and material circularity via carbon-based

These improvements may best be realized through rethinking the composition of electronic hardware from bottom to top. Carbon-based materials may offer a path, as introduced in Figure 4-1, showing a product life cycle.

The four steps are as follows:

1. Address the number and quantity of Earth resources needed for electronics.
2. Consider during design how those resources can be recovered.
3. Lengthen the product life and use phase.
4. Improve the efficiency of material recovery and create less waste.

We already cited an example of a graphene-based IC that included inductors. We can easily predict that creating capacitors like the standard construction of stacked layers of conductors and insulators may be coming, too. In fact, stacked graphene has already been investigated for supercapacitors. Making resistors—and some readers may recall traditional carbon composition types—also seems to be a natural conductor given a few modifications. Figure 4-2 shows examples of carbon-based components being developed for both active and passive functions, including transistors, integrated circuits, inductors, capacitors, and conductors.

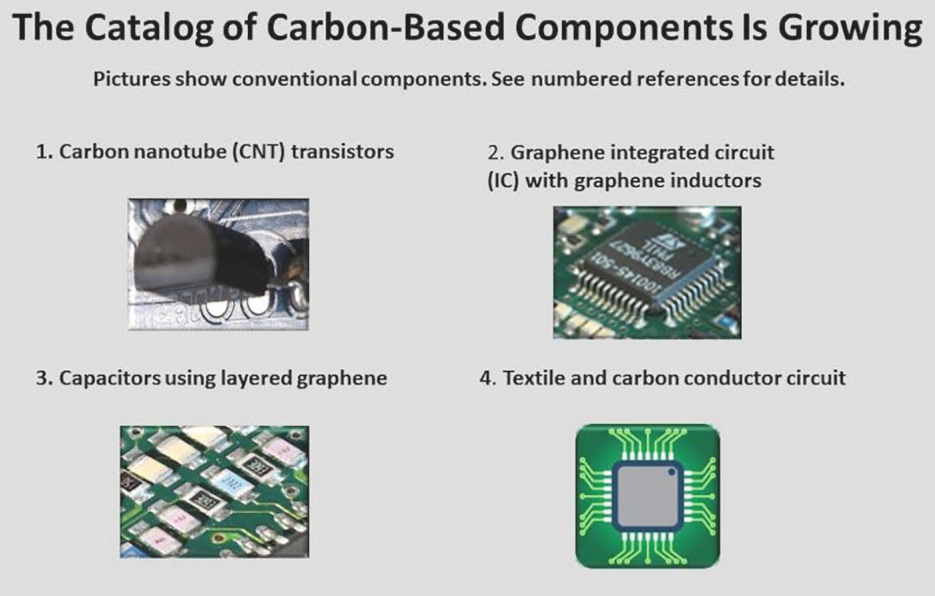


Figure 4-2 More components and circuits are now carbon-based

One of the more interesting features of graphene is its ability to behave as either a superconductor or an insulator, based on the positioning of different graphene sheets called twisted graphene (see https://www.nature.com/articles/s41563-020-00840-0. This results from a so-called "magic angle" of how the graphene sheets interact.

Though that may seem simple, the angle is critical, and this work is some years away from practical applications requiring volume manufacturing and reasonable cost. But the incentive is there, and groups like the Graphene Flagship initiative (see https://graphene-flagship.eu/), which is based in the European Union and funded by the European Commission's Horizon research program, are bringing together researchers from academia and industry to commercialize graphene in applications like memory devices and sensors, to name a few (see www.te.com/usa-en/industries/aerospace/insights/carbon-nanotube-technology.html).

Reducing the Reliance on Material Complexity

In this section, we have speculated about an electronics future built with carbon-based components, to realize active components like transistors, logic devices, and even passives like chip capacitors, inductors, and resistors. Another graphic of this vision is shown in Figure 4-3, with carbon nanotechnology at the center.

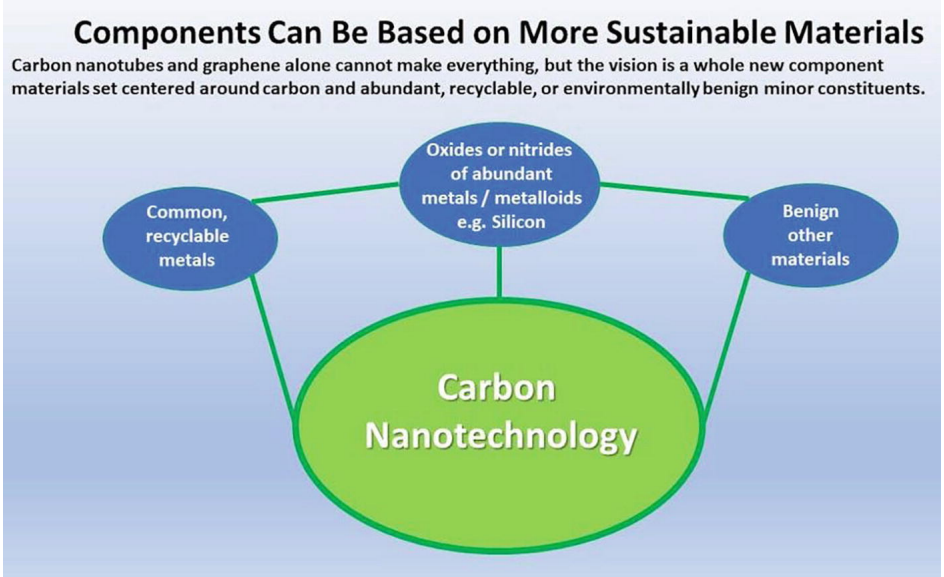


Figure 4-3 The author's vision of sustainable materials for electronic components centered around carbon

Let us reconsider carbon again, considering a few more of the principles of green chemistry. While we are not saying that demonstrating a few of these principles is the end of the story, carbon itself offers strong ways forward that basing electronics on other chemical elements or more complex mixes of many elements may not.

- Green Chemistry Principle #4, Design Benign Chemicals, has so far often resulted in the opposite: synthetic organic compounds that have very undesirable properties are reasons for being tagged as substances of very high concern. But there are some indications that developing carbon nanomaterials will be more considerate of the environmental impacts and life cycle than the last generation of electronic materials. The inherent nature of toxic heavy metals must be avoided in these next-generation materials.
- Principle #7, Use of Renewable Feedstocks, has been led by the example of nature herself. Some 170 billion tons of biomass are renewed every year. While much of this is part of the food supply, only plants can be continually regrown, unlike any other natural resource that at best can be recovered and recycled for reuse. Carbon is the most renewable element known, since even if worst comes to worst and it is incinerated (causing a different problem), it remains in the atmosphere as carbon dioxide.
- Principle #10, Design for Degradation, is the complement to being renewable in the first place. Other necessary ingredients may not be easily broken down, but if designed with the intention of making the material degradable, the carbon-based materials can be. Some of these achievements are being realized with smart polymers that have an intentional "zipper" built in for efficient degradation when the time comes.

Thanks to advances in materials like carbon nanotubes and graphene, we may someday be able to take a quantum leap toward improving the material circularity of electronic hardware, while enabling growth in new functionality. Like the system-on-chip approach and developments in conductive textiles and printed electronics, these advances may reduce reliance on so much material complexity and create more closed-loop material recovery and resource reuse.

Let us not overlook the prospects for conductive carbon itself as an alternative to copper. Carbon-based conductive polymers are being proven out in commercial applications from batteries to biosensors (see www.cas.org/resources/cas-insights/conductive-polymers?).

While we have no commercially available full-line carbon component catalog to promote here quite yet, stay tuned. Many of the components listed in the first part of this book are well under development as highlighted in this chapter, ranging from transistors to ICs to capacitors and circuits themselves. Carbon resistors are not new, and once carbon conductors are made, they can be layered into multi-layer inductors.

Carbon could be the backbone of next-generation sustainable electronics.

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For further information, see the author's video, "The future of carbon electronics," at https://youtu.be/TwKNXDon0gk and this brief article. https://www.electronicdesign.com/technologies/industrial/article/55038664/electronic-design-future-of-electronics-how-carbon-based-nanotechnology-can-lead-to-sustainable-technology

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Other Advances in Sustainable Materials

In the concluding section of this chapter, we step back for a moment from our focus on carbon to include some other important considerations. Here we offer a sustainability checklist focused on hardware, with the author's comments on progress to date, and challenges still remain.

✓ Reduction in Toxic Substances

- Thanks in large part to the EU's RoHS Directive (Restriction of Hazardous Substances) that limited the use of several toxic heavy metals with a few allowable exemptions, lead-free soldering and terminations became mainstream and significantly reduced the amount of lead in many electronic goods. Substitutes for cadmium and hexavalent chromium were also found for all but the most demanding applications (see www.eetimes.com/rohs-2-means-buyers-channel/).
- Several classes of brominated flame retardants used in plastics were also designed out to achieve compliance with RoHS. For component packages and circuit boards containing brominated or chlorinated flame retardants, halogen-free alternatives became available in conformance to standards like IEC 61249 for laminates and JS709 for components, mechanical, and circuit board assemblies.
- Flame retardants continue to be an elusive chase. While protecting against loss of life and property due to fire, which is good, finding less toxic substitutes has been difficult since, to function as desired, they also tend to be persistent, bioaccumulative, and toxic; they may also be reportable as substances of very high concern (SVHC) under the EU's REACH Directive. In all fairness, the low rating given here may be contentious since nature herself allows fires to occur, and natural forest fires are a way to start new growth.
- Many dozens of other substances used in electronic components, component packages, and related applications also are subject to regulations due to their various toxic effects. One of the new classes of substances under review has drawn attention to yet another halogen, fluorine, comprising many thousands of PFAS (per- and polyfluoroalkyl substances), as noted in Chapter 3.

✓ Plastics

- Plastics are traditionally made from nonrenewable fossil fuels. The rating again is strict, since the high-volume implementation of renewable sources for plastics in electronics remains yet to be realized. Component packages, circuit boards, and mechanical parts like housings are still largely made of fossil fuels. This may soon be turning around thanks to developments in renewable plant-based sources and controlled microbial bioreactors to make the necessary starting materials.
- Having mentioned the promise of more renewable plastics, the open end of the circular life cycle of plastics, especially engineering thermoplastics and thermosets like epoxies, is not sustainable due to poor end-of-life recovery. In some regions, bulk electronic collection and recycling does save some electronic plastics from landfill and may return some of the higher volume types to a recycling stream rather than incineration or energy recovery, or as a last resort, landfill. Even if perfectly collected and recycled, the performance of recycled plastics degrades, so the benefits are always limited unless newer technologies like chemical recycling become mainstream.
- Microplastics and even smaller nanoplastic particles have now been found across the globe, not only in oceans and drinking water, but in human tissues. So far, the volume of plastics from electronics is much smaller than that of plastics used in things like consumer packaging and one-use bags and containers, but the challenge is to never let plastics used in electronics add to this problem.

✓ Metals

- This section begins on a positive note. Thanks to electronics collection and recycling, several of the economically valuable metals like copper, silver, and gold are routinely processed in metal smelters and made available for producing new products again. Aluminum and steel, even lead in batteries, are also routinely recycled. Unlike plastics, the ability to recycle metals without degradation is good news.
- The downside here is that all the rest of the metals in components like the thin films on top of semiconductor chips are not easily separated and recovered for recycling. This problem extends to other metals like gallium and indium used in components like high-frequency chips, optical devices, and displays. Tantalum and aluminum in electrolytic capacitors pose similar challenges. And often swept into a "remainder" fraction are oxides of silicon used in glass and numerous other elements used in ceramic devices like capacitors and filters, or electromagnetic devices like inductors, relays, and motors.
- The challenges here are many, since more than 50 elements out of the 91 naturally occurring elements in the periodic table are used in electronics. According to the EPA and the United Nations, only 15% to 20% of e-waste is recycled at all. Most electronics end up in landfills or incinerators along with their unrecovered materials.

✓ Energy Efficiency and Dematerialization

- Electronics manufacturers have earned high marks here since reducing electricity consumption is a natural selling point that is reinforced by labeling programs for consumer products and appliances. The energy use of large server facilities remains a concern, so simply outsourcing and calculations to "the cloud" only moves the energy use elsewhere.
- From the perspective of using less material, which is a recognized best practice for reducing environmental impacts, the shrinking size of devices and use of software rather than hardware to achieve advanced functionality is again within the sweet spot of the industry. The use of advanced CAD systems allows engineers to optimize the use of materials and reduce weight through the process of generative design, and in some cases these systems provide choices to select raw materials having a lower carbon footprint.
- The electrification of the world to reduce carbon emissions rests squarely on the shoulders of the electronics industry. From solar and wind generation to electric vehicles, greater energy efficiency and reduced carbon footprint are being achieved. Improvements we could not imagine a few years ago are not only imaginable now but are being realized. More will be said about energy in Chapter 7.

Key Takeaways

This chapter has introduced some very promising carbon nanotechnology that could offer hope for more sustainable future electronic materials. Components that are the functional parts of all electronic goods could be made with fewer materials and leverage the common element, carbon. This alone will not solve everything since other minerals and elements will still be required, but the focus on carbon is being seen as one of the most promising roads ahead. Transforming major electronics assembly operations, including extremely expensive capital outlays like wafer fabrication plants, will not happen overnight, and while the focus of this book is not economics, changes there will certainly be critical. Besides chemicals, we also reviewed here the alignment to common principles of sustainable chemistry and some perspective on other necessary changes to reduce toxic materials; optimizing the use of both metals and plastics will still be needed. The next chapter focuses on recyclability and circularity.

For Further Reading

R. L. Franz, "Electronics advances in sustainable materials," *EE Times*, June 12, 2024. (https://www.eetimes.com/electronics-advances-in-sustainable-materials/)

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5. Recyclability and Circularity

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Thus far in our story, it should be clear that completing the circuit to sustainability is more circular and full of loops than a straight line. Beginning with some reasons to pursue sustainability in the first place leads to the need for understanding what makes up the hardware (WITS), then how we get data for that from start to finish in an extensive supply chain, how to distinguish the useful vs. the not-so-friendly contents (often in conflict for being both at the same time), then some projections about how all those materials and newly developed materials could be more sustainable.

What you will take away from this chapter

- How environmental impacts are measured with the Life Cycle Assessment
- Regional requirements to reduce waste from electrical and electronic equipment
- Specifications for recycled materials
- Transparency and reporting
- Problems with recycling today

If this were all easy, it would have already been done. Here we break down the nice idea of electronics recycling into some hard truths and incentives to keep moving ahead, whatever direction that should be for the circumstances.

The Science of Sustainability: Life Cycle Assessment (LCA)

While the next chapter goes into more detail on the available tools and systems for engineering more sustainable products, the most widely accepted methodology to evaluate environmental sustainability is to conduct a Life Cycle Assessment. Covering LCA in more detail could easily be several volumes alone, but here we summarize the key points in the context of circular electronics.

The range of impacts that human operations may have on the environment is not to be taken lightly. The following is a list of impact indicators that can result from a full LCA.

1. Climate change
2. Ozone depletion
3. Summer smog
4. Eutrophication
5. Acidification
6. Human toxicity
7. Freshwater ecotoxicity
8. Seawater ecotoxicity
9. Terrestrial ecotoxicity
10. Radioactivity
11. Land use
12. Non-renewable material resource depletion

13. Renewable material resource consumption
14. Non-renewable primary energy depletion
15. Renewable primary energy consumption
16. Particulate matter/respiratory inorganics
17. Species depletion
18. Noise

More detailed descriptions and the units of measure for each LCA impact listed here may be found at sources like Ecochain (https://ecochain.com/blog/impact-categories-lca/).

Note that these are mainly physical, chemical, and biological impacts affecting Earth's resources and life forms. If this list is not enough, some practitioners go beyond noise to include things like light pollution. Social and economic aspects are not typically assessed by LCA calculations (see Double Materiality, discussed in this chapter). On the other hand, the scope of impacts to be studied can be reduced depending on the purpose of a particular LCA, for example, to focus on climate change, toxicity, resources, or energy indicators.

LCA may also be defined to cover more or less of a full product life cycle. These are mainly

1. Raw materials
2. Product manufacturing, which may include energy consumption and emissions to air, water, or land
3. Packaging

4. Transportation

5. Use phase, including refurbishment, reuse, and so forth

6. End-of-life treatment

The first four constitute a *cradle-to-gate* scope, which includes impacts up to the point where the product leaves the manufacturer's "gate" to enter the marketplace.

Including all six steps is then a *cradle-to-grave* scope, often rephrased as a truly circular *cradle-to-cradle* assessment.

LCA is not only applicable to electronic goods; it can be used to assess any product or service. LCA studies have become a substantial body of knowledge and subject of ongoing research; for example, the *International Journal of Life Cycle Assessment* (see https://link.springer.com/journal/11367), which has been in publication since 1996. Related partnerships and societies are listed on the journal's home page.

The main steps of a complete LCA are

1. **Goal and Scope Definition.** First, the scope of the assessment needs to be defined, including which impacts will be included, as well as the overall life cycle scope. Often there are certain functional units that help define exactly what is being modeled.
2. **Life Cycle Inventory Analysis**. Here, the basic environmental impacts are calculated based on the defined inputs and outputs.
3. **Impact Assessment**. This important phase is where the environmental effects are reviewed and, if necessary, refined.
4. **Interpretation.** Finally, the conclusions can be stated to fulfill the goals and definitions of the LCA.

Life Cycle Impact Examples

The following summarizes a few LCA takeaways for three familiar products.

Furniture

For a product made primarily of wood, certainly the resource depletion impact on natural resources (trees) is expected to be significant, as well as the manufacturing phase. Such a product will not be consuming any electricity or fuel in the use phase (with the minor exception of reclining chairs that may occasionally use a motor to change position). Unlike many electronic products, the life cycles of furniture may span years or decades, and resale or donations may give the product multiple lives before the disposal phase, which might be able to reuse the wood in other applications like wood chips. Forests themselves may be sustainably managed, as measured by labels like those from the Forest Stewardship Council (FSC). Forest Stewardship Council (https://fsc.org/en/label). More complex products that may include plastics or metal then become a little more complex at the end of life, becoming more like our next example.

Automobiles

The demands for raw materials and manufacturing for a vehicle are extensive, to say the least, ranging from metals like steel and aluminum, various plastics, fabrics, glass, rubber, and increasingly, electronics. Unlike furniture, however, the use phase for a gasoline-powered vehicle may dominate the overall impact resulting from non-renewable energy and material consumption, plus impacts to air quality and climate change. The proportion of these impacts will change for an electric vehicle, which nonetheless will have its own demands on dissimilar materials, notably for batteries and motors. More will be said about these areas in Chapter 7.

Personal Computer

A “hot spot” analysis of the main contributors leads to concern over the many raw material resources needed for today’s high-tech products, some of them having toxic properties as we have discussed at length, and somewhat effective but imperfect recovery and recycling processes at end of life. Energy will also enter the picture, including both electricity from the grid and battery power. Silicon device fabrication has great demands on exotic chemicals and energy, including strict internal environment control for clean rooms. It is these kinds of issues that have led to the need for the present book.

Double Materiality: Socio-Economic Assessment

Before we go into more detail about hardware sustainability, mention should be made of the social aspects not considered in detail here. This is usually performed as a Double Materiality Assessment, which actually is *not* about the materials in electronics hardware. Rather, as stated by the Global Reporting Initiative (GRI) (see www.globalreporting.org/media/jrbntbyv/griwhitepaper-publications.pdf). “Materiality is a socio-economic and political, rather than a technical, phenomenon.” As such, it involves the interplay of company operations and finances, although it is not just financial reporting. In the European Union (EU), the Corporate Sustainability Reporting Directive (CSRD) (https://csrd-directive.eu/) “…encourages businesses to evaluate not just how sustainability impacts their bottom line, but also how their operations affect the environment and society.” Practically speaking, these types of reports are intended to improve transparency and accountability of company operations beyond the bottom line of making a profit.

LCA-Related Steps

Before initiating an LCA study, a common first step is to know if the specific type of product already has defined Product Category Rules (PCRs), which vary widely among different products. On the results and reporting side, if the intent is to publish the results, a third acronym will be involved: the Environmental Product Declaration (EPD) (see

www.epa.gov/system/files/documents/2024-11/epd_basics_how_why_to_develop.pdf). Performing the LCA is then the middle step.

PCRs are a kind of document that defines how the LCA should be conducted. ISO 14025–compliant EPDs summarize an LCA that was created following an applicable PCR. The ISO (International Organization for Standardization) and related standards will be covered in the next chapter. For our purposes here, the series of PCR to LCA to EPD does not actually improve anything; they measure the state of the current product. However, knowing where you are at provides a baseline for improving the weak points, which again depends on the kind of product.

Given the inputs that describe the product, depending on the software tools used, a common output of an LCA is a Sankey diagram. This visual flow diagram typically uses the width of each flow line to show its relative impact on the overall process or product.

As an interesting side note, how technology evolves by building on itself is illustrated by the history that the Sankey diagram is named after Irish Captain Matthew Sankey, who used this type of diagram in 1898 to show the energy efficiency of a steam engine. (See A. B. W. Kennedy and H. R. Sankey, "The Thermal Efficiency of Steam Engines," Min. Proc. Inst. Civ. Eng., vol. 134, pp. 278–312, 1898. Available at https://zenodo.org/record/2036163.) It is still applicable to any LCA calculation today.

- This type of analysis leads to a few scenarios and opportunities. How can the impact of the materials directly made into the product be reduced by using alternate materials, fewer of them, or less of them, to enable more efficiency and the need for less new starting material?
- What complex components could be simplified to a single material that would make the recovery step more efficient?
- Better yet, what if the insulation could be made of a more recyclable material?

- Also, what if the components could be made of more renewable materials, such as a bio-based plastic like polypropylene? (See www.mdpi.com/2073-4360/12/8/1641.) This would reduce the initial raw material impact, although not necessarily improve its ultimate recyclability.
- Both renewable and recyclable materials, components, and complex assemblies would be better, but probably not possible today.
- While the copper should be recyclable, what if the conductor and insulator were *both* carbon-based, enabled by some future nanotechnology?

Practically speaking, in discussing current recycling practices with actual recyclers on the ground, large volumes of insulated wire could be stripped to yield a purer copper fraction which has more value on a weight basis than when diluted with non-metals. Plastic insulation is unlikely to have a good recycling path. If the stripping scenario is not possible, nonetheless the copper may well find its way to a copper smelter to be reused. Imperfect at best because no means to "unmanufacture" the extrusion of plastic on a conductor was ever considered.

While we will highlight current best practices in recycling electronic hardware, recent products have been designed for disposal, rather than recyclability, longevity, or repairability. Hence, many of the lessons and best practices in this book remain to hit the mainstream.

LCA tools, especially for product engineering, typically use the bill of materials (BOM) for the design as the input, which has the advantage of allowing trade-off analysis of different material and assembly strategies ahead of the more formal PCR-LCA-EPD sequence on a finished product. More on this approach is covered in Chapter 6. It is early in the product design phase where the preceding scenarios should be considered.

Looking at the far right of the diagram, the good news is that copper is a good example of a circular material. These are representative LCA datasets listed by ecoQuery:

- treatment of electronics scrap, metals recovery in copper smelter
- treatment of metal part of electronics scrap, in copper, anode, by electrolytic refining
- treatment of precious metal from electronics scrap

Here, we are mainly discussing electronics, but it is worth noting that copper in car shredder residue has an LCA dataset, and there are similar datasets for steel, aluminum, zinc, and lead in car shredder residue. The supply chain providing electrical and electronics content to the worldwide vehicle market is significant.

This means that the LCA of such metals may be expected to calculate some recovery of impacts to reduce applicable eco-impacts. Simply put, this is good.

Polyvinyl chloride (PVC) and the additives are much more of a problem. Unlike copper, no such scrap modeling scenario is found for PVC or most other plastics. For comparison, occasionally a plastic like polyurethane may have an end-of-life model, although landfill is anything but a circular solution. This is the entry from the preceding ecoQuery source: "."

treatment of waste polyurethane, inert material landfillFinding an end-of-life model is generally a good thing, but unless the landfill deposit is actually a useful fertilizer or some rich organic material like humus or peat moss, let us just bluntly say that this outcome is not sustainable. Not having any place to go for recovery is one of the biggest challenges not only for electronics but for very many products today.

A corollary to this statement is that unless a given material designed into a new product has the possibility of a circular life, it should not be designed in.

Of course, doing this is much easier said than done, which is why we spend considerable time projecting what could make up the next generation of circular electronic material to be more like nature herself. Going beyond the carbon components specifically covered in other chapters, some have broadened the term more widely to be *organic electronics*. "Organic" in chemistry is defined as the study of carbon, which may by extension include other common elements forming

compounds with carbon as found in life, like hydrogen, oxygen, nitrogen, phosphorus, sulfur, and so on.

At some point in a product life cycle, an end-of-life state will be reached. The next section introduces some important aspects of managing waste electronics in terms of best practices for legacy and current product designs and materials.

Origins of WEEE Recycling

The Waste Electrical and Electronic Equipment Directive (WEEE), effective since 2003, required the collection of end-of-life equipment in EU member states, thus ensuring incoming WEEE material streams for recycling operations. WEEE was revised in 2014 with provisions for the treatment of items including batteries, PWBs (printed wiring boards), and cables. The revisions also (1) required financing to enable free collection of WEEE from consumers; (2) required the use of the crossed-out wheelie bin label to help with separation of WEEE from other household waste; and (3) required target recycling rates, metrics, and reporting.

A significant complicating factor in any recycling regime is dealing with hazardous substances. Toxic substance reduction took a major step in 2006 with the EU's RoHS (Restriction of Hazardous Substances) Directive, which limited the use of four heavy metals—lead, cadmium, mercury, and hexavalent chromium—as well as two families of brominated flame retardants in EEE. These substance restrictions were later expanded in 2019 to cover four phthalates used as plasticizers and softening agents. These regulations helped improve but not eliminate health and safety precautions within recycling operations. In addition, they have been adopted by global electronics manufacturers, so the benefits should apply to many other regions as well.

The "Ecodesign Directive" of 2009 laid out a framework to accomplish reuse of operational equipment first, followed by recycling and recovery of materials and/or energy. One of the main themes of the directive was for designers of EEE goods to consider the entire life cycle of the product, including how it could be properly treated at the end of

its useful life. In addition to binding requirements in the Ecodesign Directive, several voluntary certifications and eco-label programs were adopted widely, such as the Electronic Product Environmental Assessment Tool, or EPEAT (www.epeat.net/), administered by the Global Electronics Council. Programs such as these have improved the environmental performance of high-volume products and made these features more transparent to the user. The products covered by EPEAT at this time are computers and displays, imaging equipment, mobile phones, photovoltaic modules and inverters, servers, and televisions.

For a manufacturer to receive EPEAT certification, a points system is used to score the product in different categories ranking environmental considerations:

- reduction or elimination of environmentally sensitive materials
- materials selection for least overall environmental impact
- design for end of life
- end-of-life management by the manufacturer

Because avoiding toxic substances is a requirement to receive EPEAT certification, certification is not always possible with today's limited choices of certain components and materials. While many high-volume products are covered by EPEAT, clearly many other equipment categories are not. Other types of eco-labels and environmental product declarations continue to develop for other kinds of products. The important message is that all these incentives are in the best interest of recyclers because they help improve the recyclability of products and control hazardous substance content.

Responsible manufacturers work to select components and materials with minimal environmental impact, obtaining environmental product certifications and declarations where possible and if applicable. More generally, manufacturers attempt to communicate their commitment to recognize and publicly track progress through their own sustainability, corporate citizenship, and product stewardship programs. As part of these efforts, manufacturers might impose strict supplier requirements covering the same concerns.

Current State of Circular Electronics

There is a strong connection between the many elements and materials discussed in previous chapters and the need for more sustainable electronics. Metals recycling is currently practiced in many countries, driven by the economic value of gold, silver, copper, aluminum, tin, and down the list to diminishing returns for the many other dozens of metals currently used.

From a practical perspective, electronics recycling has already been developed at least to the level of operational commercial recycling paths. It may not be surprising that precious metals in copper are the key materials used to drive economic recycling of today's products. (See www.isrispecs.org/wp-content/uploads/2023/05/ISRI-Scrap-Specifications-Circular-updated-1.pdf.)

The ReMA Specifications Circular (www.isri.org/recycled-commodities/isri-specifications-circular) provides guidelines for buying and selling a variety of other processed scrap commodities, including ferrous and nonferrous metals, paper, plastics, electronics, rubber, and glass. Of interest are related electrical materials like Shredded Insulated Copper Wire (see www.isrispecs.org/orpheus_resource/shredded-insulated-copper-wire/), given the name of Zeyda. The source states the following about it:

> "Shall consist predominantly of recovered ICW (Insulated Copper Wire) that has been derived from either mechanical or physical separation. This material is likely to have other metals, in small percentages (should be less than 5%), that were not successfully separated. The percentage of each metal within the overall product shall be subject to agreement between buyer and seller. Shall have passed one or more magnets to reduce or eliminate free iron and/or large iron attachments. Shall be free of radioactive material, dross, or ash. Material to be bought/sold under this guideline shall be identified as "Zeyda" with two

numbers to follow, indicating the estimated percentage of recoverable copper wire and the second indicating the maximum amount of other metals or contaminants expected. (e.g., "Zeyda 45/3" means the material contains approximately 45% copper and up to 3% other material). May also be screened to permit description by specific size ranges."

Once again, the copper is accounted for, which in the case of electrical wire is most likely fairly pure copper free of other metal contaminants, but once again the "other material" fraction seems to be in need of a better circular solution.

Possibilities for the "other" stuff may include processes to treat complex organic waste in a bioreactor to yield useful chemicals which could become the recycled feedstock for new materials. The key here, of course, is the composition of the feedstock, which ideally could be quite easily processed, like in a natural compost to degrade by natural processes. Other approaches include conversion of mixed organic waste to energy by combustion, and although not preferable, it does help provide energy rather than becoming less useful as landfill.

The promise of completely organic electronics is becoming more interesting to resolve the problem of conductors and insulators being opposing kinds of materials.

A circular product designer today should be aware of existing end-of-life specifications and try to meet or exceed the requirements, not the least of which are limits on various types of contamination due to unwanted materials. Unfortunately, if asked to design an electronic product that exceeds these criteria, including where the plastics end up, today's engineer will simply not have sufficient choices available.

To compound the problems even beyond these more recoverable metals, many others like the rare earths beg for technology to recover them. In fact, true circularity will never be accomplished if one considers the complexity of native ores which, once refined, have no practical chance of being returned to Earth as they were found. We will be satisfied to have the once-refined metals returned to a refined state

to be used over and over again as a closed loop, even if a smaller-than-perfect circle.

Plastics recycling is imperfect at best since, unlike metals, polymer chains degrade upon recycling. This is one reason that even captive regrind, where the leftovers from a given industrial molding process are reused again for the same process, has a percentage maximum as determined by engineering requirements. For common consumer plastics and larger plastic parts like cases and housings, some recycling is possible. Examples include polycarbonate and ABS (acrylonitrile butadiene styrene) or their blends (PC-ABS). This is one reason that standards have specified marking of plastic parts with their resin type, and automated means like infrared spectroscopy have been used for some high-volume sorting of electronics waste. Unfortunately, the author has found little progress in the recycling of engineering plastics or thermosets like epoxy or polyurethane. Some hints on progress will be noted later in this chapter.

Bio-based plastics have been proposed as a solution, but while helping to reduce the supply-side dependence on fossil fuels, they may in some cases compete with food supplies and, on a large scale, have adverse effects on environmental degradation like deforestation and water use. Using other sources like agricultural waste or lignin from trees may hold promise. Even so, a bio-based plastic that is the exact equivalent of the fossil fuel-based polymer does not address the end-of-life cycle at all.

Chemical Recycling

The shortcomings of today's plastic recycling processes are widely recognized. (See www.reworldwaste.com/news-and-resources/blog/we-need-to-modernize-mixed-plastic-recycling.)

The difficulties are compounded for electronic goods where multiple engineering plastics and metals are tightly bound together to create functional, reliable products. Even so, physical recycling of plastic is not perfect either, since processing will reduce the chain

length of the polymer and degrade the material's properties. This is the reason that plastics reground and reused in a factory to make the same parts where it was originally used will probably be limited to some percentage of virgin plastic. Chemical recycling is another possible solution to recovering carbon-based plastics. Several options are developing into commercial processes. These include the following:

- Depolymerization of the long-chain plastics into individual monomeric chemicals which can be further refined and returned to industry, somewhat analogous to the processing of crude oil
- Minimal refining of the depolymerized plastic to create mixed fuel which can be resold and reused as such
- Incinerating the material to generate electricity directly

The last two options do not perfectly resolve the goal of achieving true material circularity but do help extend the life of the waste material and divert it from landfill.

While most plastics do not naturally biodegrade over reasonable periods of time, the right kind of chemical processing could depolymerize a given plastic back to individual smaller molecules as starting materials for making new materials. In one sense, this approach is similar to extracting useful chemicals from the mixture of crude oil. Any such processing will also bring its own impacts on the use of other processing chemicals and demands on energy. Ultimately, it will require LCA to validate that such methods have a net gain.

Engineering plastics are the main concern here. It has been reported that engineering-grade polymers of interest, including poly(phenylene sulfide) (PPS), poly(aryl ether)s including poly(ether ether ketone) (PEEK), polysulfone (PSU), polyphenylsulfone (PPSU), and polyethersulfone (PES), are under study, and such chemical treatment deserves further work. If metal content can be retained and sent for separate processing, such treatment of mixed electronic scrap could be improved compared to current practices. (See, for example, B. Gu, R. Huang, Y. Zhao, and X. Jiang, "Depolymerization and Functionalization of Super Engineering Plastics," *Chin. J. Polym. Sci.*, vol.

43, no. 7, pp. 876–886, Jul. 2025, doi:10.1007/s10118-024-3226-1. Available at https://link.springer.com/article/10.1007/s10118-024-3226-1.)

Avoiding landfills for materials like plastics presents other options, for example, converting waste to energy. One such process operated by Reworld, a company with more than 100 locations and 4,000 employees, runs as follows.

Some initial sorting may be applied, following which the material is incinerated at an elevated temperature (2,000 degrees Fahrenheit), generating steam in reactor tubes that turns a turbine and generates electricity, which is returned to the grid. The steam is then condensed back to water and reused in a closed loop, while mitigation of acids and particulates during combustion is accomplished by chemical neutralization and baghouses, respectively. In this way, up to 99% of the material is converted to energy, while remaining solids are further separated by magnets for ferrous metals and eddy current for nonferrous metals like copper and aluminum, which are then recovered in a metal smelter.

A video provided by Reworld is also available at www.youtube.com/watch?v=RAXbohaBGt8.

We have already covered the negative aspects of many plastic additives, including flame retardants and plasticizers. Such additives do fulfill their useful functions but were never expected to be sustainable in the first place.

Among the main elements of sustainability, using less material through miniaturization and reusing manufacturing waste is already possible. Material substitution to reduce toxicity and reliance on non-renewable resources is possible in limited cases, but not as easy as highlighted by examples we have shown. Designing for modularity and ease of reuse is possible to a limited extent, but most components that must function reliably will not simply be reusable in most cases.

A study on “The Economics of Electronic Component Salvage and Reuse” (see www.circuitrework.com/tech-

papers/1747052581.html) provides some cost recovery figures for removal of components soldered in place. The authors conclude that "While the economics of reclaiming many low-cost components may not offer a positive return, there is a clear value proposition in reclaiming electronic components with higher values, including microprocessors, microcontrollers, and artificial intelligence semiconductor chips," but that the success of such practices would be limited by the need for quality standards.

What will happen may depend on whether it is voluntary or required. Sometimes it takes some external pushing to make things move along.

No Longer Optional

Reporting the environmental status of a product is becoming more of a mandatory requirement than voluntary. The EU's draft Proposal for Ecodesign for Sustainable Products Regulation would require this passport information about a product to travel with it throughout its life cycle until the item is ready for recycling.

The European Commission released the Circular Economy Act (https://environment.ec.europa.eu/strategy/circular-economy_en) *for a cleaner and more competitive Europe*, along with the Circular Economy Action Plan (https://environment.ec.europa.eu/topics/circular-economy-topics/first-circular-economy-action-plan_en).

Two key aspects of the directives are reducing the carbon footprints of products to address climate change and requiring assessment and reporting of the overall life cycle of materials through their ultimate end-of-life treatment.

This last step is clearly of significant importance to recycling companies. As part of the European Green Deal, the European Commission has created a Circular Economy Action Plan that will help enforce the closed loop of materials recycling in the region.

The requirement for a digital product passport to accompany each product could bring the need to improve recycling and circularity more into the open. Continuing with our theme of the need for new, more sustainable electronic materials, here we bump head-first into pending regulations intended to enforce exactly that.

By contrast, the United States has turned away from such legislation, with the proposal for a Green New Deal not even being brought up for a vote. The direction here is clearly not forward or in any way committed to a circular economy. Global companies may nonetheless elect to adopt more sustainable operations and products to better serve global markets and satisfy customers. In the meantime, the European Union has plans to promote and extend its action plan to broader regions.

Previous chapters have explained the EU's mandatory reporting of substances of very high concern (SVHCs) under the Waste Framework Directive. Only substances listed under the EU's REACH (Registration, Evaluation, Authorisation and Restriction of CHemicals) regulation need to be reported. While serving its intended purpose and containing millions of entries, unfortunately, the Substances Contained in Products (SCIP) does not cover the other contents of products that could include valuable and highly recyclable metals such as aluminum, steel, copper, or gold. It also lacks additional information about the product and its optimum end-of-life treatment.

Between the disclosure of substances of concern to the public SCIP database and further reporting requirements like the DPP, more aspects of the shortcomings of today's electronics from a circularity and sustainability point of view should be expected to drive improvements once the truth becomes more transparent and visible to everyone.

Circular economy legislation would help enforce recycling of all kinds of goods, with a few kinds of products required to be implemented initially. The circular economy concept now has a new regulatory face with more specific plans and requirements to bring new life to recycling. More than ever, the consumption phase would hand off

to recycling rather than to landfill and/or incineration, completing the circular loop back to reusable resources.

Passports Required

The draft proposal for Ecodesign for Sustainable Products Regulation would require information about the product that travels with it throughout its life cycle until the item is ready for recycling—a kind of digital product passport (DPP) (see https://passporteu.org/).

Among other data, the DPP would include the presence of substances of concern and information to guide recycling. The following is a full list as provided in the proposed EU Ecodesign regulation (see https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en):

Article 1 Subject matter and scope.

1. This Regulation establishes a framework to improve the environmental sustainability of products and to ensure free movement in the internal market by setting eco-design requirements that products shall fulfill to be placed on the market or put into service. Those eco-design requirements, which shall be further elaborated by the Commission in delegated acts, relate to:

   (a) product durability and reliability;

   (b) product reusability;

   (c) product upgradability, reparability, maintenance, and refurbishment;

   (d) the presence of substances of concern in products;

   (e) product energy and resource efficiency;

   (f) recycled content in products;

(g) product remanufacturing and recycling;

(h) products' carbon and environmental footprints;

(i) products' expected generation of waste materials.

> "This Regulation also establishes a digital product passport ('product passport'), provides for the setting of mandatory green public procurement criteria and creates a framework to prevent unsold consumer products from being destroyed.
>
> This Regulation shall apply to any physical good that is placed on the market or put into service, including components and intermediate products."

Excluded are food and feed, living plants and animals, and medicinal products.

Substances of concern, as well as recycling guidelines, are key areas where information linked to a complex product would be made available for access anywhere through digital technology.

How will this be done? used. While not yet certain, some kind of extension to familiar computer-readable product codes could be used. One of the general approaches still being defined is how the data would be communicated across global computer networks based on some identification of the product itself. (See www.gs1us.org/.)

There are many examples of familiar and successful product identifiers. The idea would be that information relevant to the circular economy would be retrieved easily by reading a similar code to be used not only by consumers but also by parties needing to know more about the contents and manufacturers' instructions for recycling.

The new DPP requirements became effective sometime after 2024, with initial product categories including textiles, construction, industrial, and electric vehicle batteries. One more category, such as consumer electronics or packaging, would also be included.

Batteries Have a Head Start

With the electrification of vehicles and the growth of battery-powered consumer electronics already in full swing, it is not surprising that batteries were selected for early implementation of the DPP. As will be expected of other types of products with some variation, the data that would be made available in a battery DPP would include the following:

- source of materials
- carbon footprint
- recycled materials with percentages used
- product durability
- guidelines on repurposing or remanufacturing, if applicable
- guidelines on optimum material recycling

Recycling of rechargeable batteries, of course, is already well-established in the EU member states through EUCOBAT (www.eucobat.eu/), the European association of national collection schemes for batteries.

Collection and recycling support in the United States has also been available for two decades now through Rechargeable Battery Recycling Corp.'s Call2Recycle (www.call2recycle.org/).

Although the focus here is on the European Union and the United States, it seems likely that similar coverage will continue to extend to other regions in the coming years. It might be expected that the addition of DPP information could improve but not revolutionize existing battery recycling.

For more about the challenges of batteries, see Chapter 7.

Packaging and Plastics

It is less clear at this time how DPP information would improve this sector since the existing Society of the Plastics Industry, now the Plastics Industry Association (www.plasticsindustry.org/), has plastic recycling codes. Codes No. 1 through No. 7 have been in place for quite some time. Adding additional digital information on No. 6, polystyrene, for example, could hardly be expected to magically make it recyclable. The same goes for the "Misc." code, No. 7. Even No. 1, polyethylene terephthalate, or PET, which is to be recyclable, might see little benefit from more digital data.

Ripple Effects

The development and entry into force of DPPs would have direct impacts on companies in EU member states with ripple effects felt globally. While the detailed regulations have yet to be completed, the outlook is positive for recycling companies that would be able to freely access information about product contents and recycling guidelines. Where this will make sense for all types of products, it might become a question of value yet to be confirmed in practice. One might question whether the passport would improve upon the use of plastic packaging codes already in place. In general, though, the prospects to freely communicate information associated with products to effectively track and manage sustainability are positive.

For electrical and electronic equipment, opportunities could arise to improve upon the ability to better handle substances of concern but also to gain visibility into valuable and recyclable metals that otherwise would be submitted to a less-optimum, generic shred-and-send-to-smelter scenario.

Much of the success of these passports will depend on original equipment manufacturers conducting LCAs and end-of-life models during the product design phase to optimize disassembly and sorting for circular recovery, then incorporating that information into the DPP. (See www.recyclingtoday.com/article/eu-scip-hazardous-substances-weee and

www.recyclingtoday.com/article/eu-digital-product-passport-end-of-life/.)

More Perspectives on Making Electronic Products More Recyclable

Contamination of an otherwise recoverable end-of-life material by undesirable contents is an impediment to recycling. Some understanding can help raise awareness of the substances of concern designed into products and how they impact recycling and the circular economy. Bigger changes will be required to achieve fundamental changes to the material set used to make electronic hardware in the first place. But in this section, we stick to the state of play today. One of the first obstacles to deal with is what to do with substances of concern at the end-of-life phase.

What you will learn

- Which SVHC metals and non-metals currently have no commercially viable alternatives
- Issues with meeting EPEAT certifications and maintaining product design performance
- Basic principles for electronic recycling

Some of the key goals of a circular economy include reducing the hazardous substances that may end up as waste by supporting the substitution of substances of concern, and making information on product content available to waste treatment operators and recyclers. (See C. Hagelüken, J. U. Lee-Shin, A. Carpentier, and C. Heron, "The EU Circular Economy and Its Relevance to Metal Recycling," *Recycling*, vol. 1, no. 2, pp. 242–253, Sep. 2016, doi:10.3390/recycling1020242. Available at www.mdpi.com/2313-4321/1/2/242.)

Voluntary environmental certification programs for certain products are also in place—and, in fact, are not voluntary at all if the customer requires compliance with them for procurement. Among them is the EPEAT program for high-tech electronics managed by the

Global Electronics Council. The following types of equipment are currently covered, listed here with their associated industry standards.

These types of certifications use a series of evaluations that allow the manufacturer to earn points to meet minimum criteria. The questions include attention to materials selection during product design to avoid toxic substances and materials, and consideration for other types of negative environmental impact. The ability of the product to be reused and then recycled at end-of-life is another category of earning points toward certification.

Ten groups of substances have already been regulated to less than 0.1% (0.01% for cadmium and its compounds) by the EU's RoHS Directive. Since many manufacturers operate globally, these restrictions have been widely adopted by major original equipment manufacturers (OEMs).

However, for companies that are not doing business in the EU marketplace, and in fact all who require the use of RoHS exemptions for product performance and reliability, some hazardous substances may still be present. Most of the remaining substances cannot simply be designed out or replaced with choices available to today's product designer.

To review, as of January 2021, products entering the EU market must publicly declare SVHCs to the public SCIP database (see www.electronicdesign.com/industrial-automation/article/21136628/new-eu-reporting-requirements-for-substances-of-very-high-concern).

To the electronics engineer: you will probably and understandably avoid looking up the full SVHC list of over 250 such substances under the EU REACH Directive (see https://echa.europa.eu/candidate-list-table). But chances are that someone in your company will, and what follows is offered as practical information that you should know now.

A Closer Look at SVHC Impediments to Recycling

Two metals, lead and cadmium, are both banned by RoHS with a few exemptions and listed as SVHC under REACH. However, they are still needed in lesser amounts for specific types of device performance and reliability that may be allowed under specific RoHS exemptions. Here is a brief list of some of the more common usages of these metals in component parts for which there are presently no commercially viable substitutes:

- Lead in machinable steel alloys up to 0.35% per homogeneous material.
- Lead in machinable aluminum alloys up to 0.4% per homogeneous material.
- Lead in copper alloys like brass up to 4.0% per homogeneous material.
- Lead in glass, in which case lead is present in an oxidized form combined with other substances bound within the glass.
- Lead in high-temperature solder, used for reliability in components like power semiconductors, and in applications where a two-temperature soldering process is required.
- Lead in ceramic components like lead zirconium-titanate (PZT) piezoelectric sensors and transducers.
- Cadmium in alloys like silver cadmium oxide for high-current switches and relay contacts.

Non-metals that are SVHCs may also be found in certain applications:

- Remaining non-RoHS-restricted phthalate plasticizers in soft materials and polymers like polyvinyl chloride (PVC) typically include wire and cable insulation and gaskets.
- Various plastics may require the use of flame retardants for fire safety that are SVHC but not the RoHS-restricted type. Dechlorane Plus is one example.
- Siloxanes (called D4, D5, and D6) that are low-level residues from the manufacturing of polysiloxane polymers may be found in gaskets and sealants.

- Perfluoro compounds, such as perfluorobutane sulfonic acid (PFBS), may remain in lesser amounts from the manufacturing of non-stick, self-lubricating plastics or other end products that contain fluoropolymers.
- Even engineering thermoplastics that are otherwise free of SVHC may contain lesser amounts of a PFAS polymer, such as PTFE.

These substances are mentioned because they provide useful properties to make products work and be reliable. Realizing electronic goods without them is a significant challenge, and changing the current material set is not easy, even by working to substitute one substance at a time. A new generation designed from the ground up to be free of substances of concern must be the goal. Another way to state the current gap is how to return complicated materials back into something more closely representing their origins.

Design for Environment Gaps

Environmental product certifications like EPEAT require that the life cycle aspects of the product be considered, including end-of-life and materials recovery. At the product level, the designer is faced with limited choices when it comes to ensuring that, first, the product will perform as intended in the field and meet its stated reliability goals. Even basic consumer electronics goods must withstand some shock and vibration, variations in temperature, and so on.

This raises a fundamental engineering challenge: How to ensure the integrity of the product during use yet allow it to be easily disassembled and fractionated into separate materials by a recycler.

At the component level, including passives, connectors, discrete semiconductors and ICs, beyond “lead-free” terminations, and some devices inherently containing no SVHC at all, components designed with truly sustainable materials are not available yet. Consider the nature of the integrated circuit itself: Multiple materials are deposited as thin films onto a substrate, typically silicon, which is further packaged in a housing of thermoset plastic with a metal lead frame or

solderable bumps. There is no practical choice on the market for a "recyclable" component, at least not now.

Similarly, the designer has few, if any, choices in printed wiring board (PWB) selection. Some choices are available in the flame retardant used that may avoid bromine or other halogens. Research has been done on expensive processes to separate the glass filler and metals from the PWB itself to chemically recycle the laminate, but these processes are not yet widely adopted, and even so are intended to deal with today's materials. Flexible circuits may be mounted directly to a metal housing, which has disassembly problems of its own. And a traditional hybrid has the same problems with diverse materials typically adhered to an alumina substrate. Even if a main PWB assembly itself can be made removable, manual disassembly is not likely in a practical high-volume recycling operation, especially for smaller products.

Today's products with glass displays also present the problem of recycling the glass itself, not to mention thin-film semiconductors like LEDs that are integral to displays. A similar dilemma exists with touchscreens using visually transparent indium-tin-oxide capacitive touch sensors.

Only larger products with separate metal enclosures are better from the perspective of separation into useful recycling streams before further processing, while this success remains limited to the enclosure rather than the complex electronics at the heart of the product.

The amazing things that electronics can do were never designed to be recyclable.

No Easy Solutions

The fundamental issue with recyclable electronics is really the need to have both conductors (or semiconductors) and insulators present at the same time to make the product function. One without the other cannot even enable basic electricity to work safely. And for practical products, they must be in close and robust contact either through internal manufacturing processes, molding, extrusion, or assembly with

solder or adhesives. The list of contents, if much more complex than that, makes the business of "recycling" much more complex to achieve than simply saying it.

Conductors tend to be based on metals, while insulators are carbon-based (defined as "organic" by chemists). What if the conductive materials could also be based on carbon? In fact, such materials are being researched and include candidates like carbon nanotubes; polymers like polyacetylene, polypyrrole, polyaniline, polyphenylene sulfide, PEDOT (poly(3,4-ethylenedioxythiophene)); and TCNQ (tetracyanoquinodimethane). Organic transistors are being developed —in 3D no less (see www.science.org/doi/10.1126/science.adx4514).

Besides the fact that those innovative approaches are not ready to be picked up and used by the designer, they would bring another even worse outcome—now they could not readily be separated at all for recycling, unlike metallic and organic materials. Plastic materials with conductive properties would have limited reuse potential. But being organic and made of common elements just like life may be our best hope to avoid the unsustainable use of other minerals and their elements; could completely organic electronics resolve the arrow of opposites?

Speculating on Future Electronics Materials

To help resolve the conflict between conductive metals and the other opposite materials needed for electronics to function, several possibilities in the realm of carbon, carbon nanomaterials, and even the wider approach of organic electronics hold great promise. It is not expected that carbon alone could meet all the demands of functioning electronics, but by comparison, life on Earth is carbon-based, although it too has some necessary complexity. These are the commonly recognized essential trace minerals for human health.

- **Iron**: Vital for oxygen transport in the blood, energy production, and immune function.

- **Copper**: Essential for red blood cell production, connective tissue formation, and iron metabolism.
- **Zinc**: Supports the immune system, wound healing, and DNA synthesis.
- **Selenium**: Acts as an antioxidant, protecting cells from damage and supporting thyroid health.
- **Iodine**: Necessary for thyroid hormone production, which regulates metabolism and growth.
- **Manganese**: Involved in bone formation, blood clotting, and the metabolism of carbohydrates, proteins, and fats.
- **Fluoride**: Strengthens teeth and bones and helps prevent dental cavities.
- **Chromium**: Helps regulate blood sugar levels and supports insulin function.

It is important to keep in mind the word "trace." On a basic elemental level, iron is not typically a main element in electronics, but in general, in the form of steel, iron is highly recyclable. Copper has been mentioned often as the carrier for many other electronics metals, at much higher levels than trace elements, of course. Zinc is a component of some copper alloys like brass. To this list we must add magnesium, which is the center of every chlorophyll molecule used in plants for photosynthesis and might be found in larger product housings made of aluminum.

To illustrate the difficulty of a perfect and easy solution, recall that these metals were also listed as contaminants in copper-based electronic scrap: aluminum, 5%; ferrous (iron), 2%; zinc, 2%; and magnesium, 1%.

In speculating about the future of computing based on neural networks, it should also be noted that in addition to organic materials making up these cells, ions of other metals are also needed for functionality, including sodium, potassium, and calcium.

All of this could change and may need to change with a newer set of electronic materials.

Our best advice to the designers of next-generation organic electronics is to consider using life-essential metals where needed to complement the organic (carbon) materials.

Two other points must be mentioned:

- Lead, tin, cadmium, mercury, and hexavalent chromium are not on the good list of healthy trace metals!
- Millions of possible organic compounds are not inherently good or bad. They need to be studied and understood before they are manufactured and released by the tons into the environment. Benzene (C_6H_6) by itself is carcinogenic, but compounds built on the structure of benzene are found in the essential amino acids phenylalanine, tyrosine, and tryptophan, and in the nucleic acids which are the building blocks of DNA.

Basic Principles and Recommendations for Today

The keys to recycling today are based on a few basic principles that actually work as well as possible given today's set of materials.

- **Density**: The ability of hardware to be shredded and shrunk down allows for sorting into useful fractions that can be further treated for material recovery. Very low-density materials like labels and fillers can then be floated to the top or picked off the rest of the stream.
- **Temperature**: Metals melt only at high temperatures, above which most organics cannot survive without burning. The different melting properties of different metals further enable their separation back to useful pure metals or alloys by dedicated metal smelters. An all-carbon-based assembly could not take advantage of this.
- **Special properties**: Ferrous alloys can be sorted by magnets. Aluminum and other fractions are sortable with eddy-current technology. In some cases, optical sorting can be used to further sort other materials like plastics into useful fractions.

In short, using metals as conductors and carbon, glass, or ceramics as insulators does not permit perfect separation and recycling, but at least the going rate for metal scrap can give positive financial returns.

With all of this in mind, it seems we're left with these five recommendations for the electronic product designer today.

- Continue to search for the components and materials with the lowest substance of concern content and lowest environmental footprint whenever possible.
- Ask for the next generation of components and materials from your suppliers to create demand.
- Small substitutions in additives to raw materials may be possible; for example, some of the SVHC used to enhance polymer products that are not critical to performance may have alternatives available.
- Think out of the box on how your product could use totally new approaches; for example, instead of subtractive processes like machining, consider additive processes such as 3D printing.
- Every small step forward is valuable. We need momentum to take up the challenge and help blaze a bigger trail to the circular economy.

Transparency Leads to Change

Waste prevention in the design of EEE is the best approach to the extent that it can be achieved. Reuse of a functional product or its parts should be considered next. Finally, recycling and recovery are the next best approaches to minimize actual waste. A circular economy works toward efficient, closed-loop material recovery, unlike nature, which reuses matter over and over for sustaining new life.

To help achieve the framework's goals, in the 2018 update to the Waste Framework Directive, a public database was established for reporting SVHCs. The database, which contains a list of some 211 substances as of January 2021, is required by the EU REACH Directive. REACH requires manufacturers of all types of articles placed on the EU market to provide free notifications of such substances when present in articles at greater than 0.1%, along with safe use information. This new database, called SCIP (Substances of Concern in Products), went live for manufacturer reporting in January. Literally millions of articles with SVHCs have already been reported to SCIP, which includes all types of products, only some of which are EEE. According to ECHA's

"Understanding WFD" web page (https://echa.europa.eu/understanding-wfd), the SCIP database has three main objectives:

1. Decrease the generation of waste containing hazardous substances by supporting the substitution of substances of concern in articles placed on the EU market.
2. Make information available to further improve waste treatment operations.
3. Allow authorities to monitor the use of substances of concern in articles and initiate appropriate actions over the whole life cycle of articles, including at their waste stage.

The SCIP database complements the existing communication and notification obligations for products containing REACH SVHC.

In addition to "pushing for substitution" of hazardous substances in waste and generation of waste in general, an important objective is to improve waste treatment operations. That is, recycling goods, including EEE.

What SCIP Means

Given the number of products containing SVHCs already in the millions in the first month of the SCIP database's operation in 2021, it is easy to imagine that finding useful information could be overwhelming.

Through the regulatory and voluntary product certification efforts mentioned, many of the latest EEE products are now free of many SVHCs. The EU regulations have greatly reduced the toxic substance content of EEE, for example, through the use of lead-free solder. It is anticipated that some general trends will be discoverable in the massive SCIP database that could take some time and experience to fully use. When the user-accessible SCIP database goes live, please consult it directly for more specific information.

As always, the best health and safety practices in recycling operations should be followed. Some examples of helpful standards and organizations include RIOS (Recycling Industry Operating Standard) (www.rioscertification.org/); R2 (Responsible Recycling) (https://sustainableelectronics.org/r2-standard-development/); and e-Stewards (https://e-stewards.org/find-a-recycler/). Achieving certification under the ISO 14000 series of environmental management standards (see www.iso.org/iso-14001-environmental-management.html) is also a good credential for a good recycler. These provide excellent and practical guidance to implement best practices.

Conclusions

Things are improving for companies involved in recycling EEE as the circular economy grows. As we highlighted in previous chapters, knowing WITS is a first step to taking action. The SCIP database allows consumers to see what is in familiar and not so familiar products, and regulators to piece together strategies for further regulating the main categories of goods, ranging from toys and clothing to high-tech electronics and everything in between. It is a bold new step with great prospects to help us all on this small planet. Laws will push industry where volunteerism may fall short.

Perspective on Small Electronic Products

Personal devices like mobile phones may be best known "up close and personal" by many readers, so a discussion of their overall life cycle is worth highlighting here.

Early portions of this chapter were previously published by the author as "Calling for Help: From the perspective of an OEM, many issues and opportunities surround the recycling of small electronic products," *Recycling Today*, June 15, 2004 (see www.recyclingtoday.com/article/calling-for-help/)

and “The Life Cycle of Materials Mobile Phones.” UL White Paper, June, 2011 (no longer available online).

While progress is being made, many aspects remain the same since the original data referenced was collected on this subject.

The United States is not too far behind the European Union in some ways. At last count, some 36 electronics waste bills were being developed in more than 10 states. While many are focused on lead-glass-containing computer monitors and TVs, some states like New Jersey have specifically targeted cellular telephones. The implication for all electronic products is becoming increasingly clear: Recycling consumer electronics goods will be a growing business. And its efficiency needs to be improved.

Within the US recycling industry, dedicated electronics treatment facilities are rapidly developing.

Nonetheless, many OEMs, including some makers of portable devices, are still learning to manage end-of-life electronics. Portable devices are typically made up of a printed circuit board (PCB) and one or more thermoplastic and/or metal enclosures. (You can verify that this is a very popular design strategy by looking around your home, office, or even in your pocket.) Challenges involved in recycling electronics are distinctly different from the proven methods for processing paper, consumer plastics, aluminum, or steel. For instance, recovering glass from TVs or computer monitors is a distinct specialty that has recently developed.

Precious Metals

Materials with the most limited use by percentage and yet the highest economic value will drive the materials recycling process. These include precious metals, including gold, palladium, and silver, while copper is another consideration. OEMs have been fortunate that considerable compatibility exists between PCBs and existing metal smelting operations. Recovery efficiencies for copper and precious metals must be greater than 90%.

Some have considered the higher-valued PCBs to be a feedstock that is as good as or better than mined ore. Use of precious metals is required in some critical components and circuits, and palladium or silver may be used in some applications. While increasing the precious metal content would certainly favor recycling, practically speaking, cost limitations in the design will nonetheless keep their use to a minimum.

One of the main issues in PCB recycling is pretreatment. While the organic materials can be incinerated and reduced to ash before smelting to refine the metals, this leaves the majority of the low-value ash, glass filler, and ceramics from components to be treated as solid waste. New technical approaches include novel uses of progressive shredding and size reduction, in some cases employing shear-force acceleration to separate composites, followed by sorting based on density and electrostatics/electromagnetics.

The use of many chemical elements in printed circuit boards, components, and solder parallels the extent already noted from the perspective of computer chips and energy-critical materials. Dozens of reports on chemical analysis are available (see, for example, N. Korf et al., "Multi-element chemical analysis of printed circuit boards—challenges and pitfalls," Waste Manag., vol. 92, pp. 124–136, Jun. 2019, doi:10.1016/j.wasman.2019.04.061; available at https://pubmed.ncbi.nlm.nih.gov/31160021/).

As often mentioned, the main metal is copper, with very small amounts of even more valuable precious metals, like silver, gold, and palladium. Incidentally, as noted in a previous chapter, the widespread industry adoption of lead-free solder has taken effect in high volume in recent years to reduce lead content.

Today, the maximum amount of material that is recyclable from epoxy-glass PCB assemblies is limited to the dominant and recoverable precious metals, which may be only 20% to 30%. From a product design perspective, different ways of increasing the overall recycling efficiency—defined as the mass of material recycled divided by the incoming mass of product—have been identified through design-for-environment software.

One solution is that for a given design, increased use of some highly recyclable, non-PCB material, such as housings made of a single thermoplastic or, better yet, a metal alloy, can raise the overall recovery rate of the product. In other words, to offset the low recyclability of a PCB, using more recyclable material outside of the PCB can increase the overall amount of product that can be recycled.

Making circuit boards that are flexible and also transparent can be accomplished in other new ways, including making use of the native oxide film that forms on many common metals. This approach has been tried, including gallium and aluminum. Oxides of indium, most often combined with tin to make indium tin oxide, are often used in optical devices like displays, which require transparency and electrical conductivity at the same time.

One possible solution to increase the recyclability of PCBs beyond just metals is to not only use the available separation technology but to develop economically viable markets for filler materials based on epoxy, ceramic, and glass fiber mixtures. The remaining incompatible metals can be separated from each other.

An example of a relatively recyclable product we have found is a desktop battery charger with a small circuit board and relatively heavy housing made of a single recyclable thermoplastic material. However, the OEM cannot incorporate this design into many other types of products.

Plastics

Recycling of engineering thermoplastics could be enabled by high-volume streams of a single resin type, preferably of a known resin manufacturer, with known physical properties, such as Izod impact strength, uncontaminated by other materials, such as other resin types, decorative finishes, adhesives, paper labels and metal inserts. Resin color may be of secondary importance because mixed colors can generally be blended to gray and then turned black. Unfortunately, only a few of these plastics used in large products, like polycarbonate and PC/ABS blends, have commercial recovery potential.

Recycling existing plastics will never be able to go far enough because most were never designed for recycling. If only some kind of key could be included to unlock the long polymer changes on demand, to yield smaller molecules that could be used to rebuild new plastics. Some progress is being made with special enzymes—protein catalysts that do all the work in the metabolism of living creatures—to do just that. Polyurethane is one example, since recycling thermoset polyurethanes is hindered by their cross-linked structures and chemically stable urethane bonds, such that advances in biocatalytic recycling (see www.science.org/doi/10.1126/science.adw4487) are being developed as one approach. Other approaches that have been tried on polyacrylic polymers like poly(methyl methacrylate) (PMMA) have included chemical agents based on copper, iron, nickel, or silver as catalysts (see www.science.org/doi/10.1126/science.adr1637) and, even more promising, the use of visible light as the photocatalytic agent. In these examples, we see the need for metals and minerals to help with recycling plastics made mainly of carbon. We need both sides to be sustainable.

More success has been realized with consumer plastics that are very short-lived, unlike engineering plastics that must retain their properties over a wide range of temperatures, humidity, and other stresses in an electronic product. Plastics made of natural sources, that is, bioplastics, hold great promise for being designed for end-of-life decomposition but have similar shortcomings in their adoption for electronic components or other applications.

Without getting into too much detail on the chemistry of bio-based materials, such sources are very promising from a renewable resource perspective, given some precautions against their misuse, like taking away food or causing destructive changes to land and water usage. But abundant plant sources exist, including

- Crops like sugar and grains that can be fermented
- Oil-bearing seeds and plants like soybeans

- Crop residues and leftovers (bagasse)
- Woody crops yielding cellulose, hemicellulose and lignin

From these raw materials, a number of chemical processes can use them to make an almost endless variety of useful materials which, from an electronic product perspective, may include the following:

- Basic industrial chemicals (comparable to fossil fuels)
- Polymers (plastics)
- Lubricants (for moving parts like relays and many other non-electrical applications)
- Chemical energy, steam, or ultimately, electricity

(See https://onlinelibrary.wiley.com/doi/abs/10.1162/108819803323059442.)

Given these origins, in general it may be more likely that the end-of-life products so fabricated could be more sustainable, similarly to how trees decay in a forest or other food scraps are turned into useful soil nutrients in a compost. While these are mostly still dreams until component and circuit designers have catalogs of such hardware to choose from, these are valid future goals.

Green Plastics: An Introduction to the New Science of Biodegradable Plastics by E. S. Stevens (Princeton University Press, 2002) highlighted much of the work in this area and concluded at its time of publication that "...there is no magic bullet in the field of bioplastics" (see p. 151) and that fundamental change in our overall approach to plastics needs to change since "if there is no paradigm shift, bioplastics will only find their way into easy "niche" markets" (see p. 159).

The following summarizes the challenges:

- If the source of biomaterial is renewable, does it compete with food supplies and/or cause other undesirable eco-impacts?
- Is the resulting polymer truly biodegradable, and by what standards is it measured?

- Is bioplastic robust enough to replace existing engineering thermoplastics?
- How can the overall life cycle management of plastics be more holistic, or will this lead us back to other materials altogether, like lignin from trees or bio-engineered wood?

The volume of the electronics waste stream is another key issue. Recycling consumer packaging that tends to be mostly a single material is only somewhat successful today. Plastics used in electronic goods are much more diverse and much more difficult to separate into clean polymer types for further processing.

There have been many efforts to make thermoplastic recycling more successful. The National Center for Electronics Recycling (NCER) (www.electronicsrecycling.org) notes that both manual dismantling to demanufacture the product into fractions with similar contents to optimize recycling, and mechanical shredding to continue the size reduction process, are in use today. As always, reusing the item as a functional product or module of a larger product is the preferred first choice whenever possible. And as noted so frequently in the present book, these processes must deal with products not optimized for sustainability in the first place.

What About Silicones?

Silicones, siloxanes, and similar materials are used widely as potting materials, encapsulants, insulators, and so on. While their end-of-life treatment does not seem to get as much attention as plastics, some work is underway to improve how these materials can be recovered rather than landfilled. These polymers in many ways present similar problems to thermoplastics, except that their chemical backbone is silicon rather than carbon.

Chemical methods have been used, as have mechanical means to grind up and reuse in other applications. Just like plastics, complexity of the recycling stream leads to contamination, which reduces the effectiveness of either approach.

Here, let us look at an example of chemical recycling using the familiar gallium as a catalyst. A 2025 research report (see www.electronicsrecycling.org) claims "…an effective method for depolymerization of nearly any silicone polymers…" and "…paves the road for the circular economy of silicon…" The catalyst here is the metal gallium.

This kind of research should be encouraged toward realizing success on commercial and economic scales.

Working Together

Equipment manufacturers can certainly use the help of electronics recyclers.

First, it is given that all regulatory agencies and company-specific requirements must be followed. Nothing will stop a business relationship faster than failing to honor certificates of destruction or having an environmental compliance issue.

Second, integrity in the sampling and accounting procedures is a must. OEMs know the content of their products. Data is being developed to track the content of products according to established specifications. For more information, see Chapter 2.

Finally, ongoing feedback on recycling results is needed. As we enter a new area of closed-loop product stewardship, it appears that this can happen. One of the most available and practical ways to extend the life of your personal electronic devices like cell phones, tablets, and computers is through manufacturer rebates that may be available, after which the product is refurbished and placed back on the market. As mentioned elsewhere, the rate at which the hardware becomes out of date, unfashionable, or even incapable of being brought up to date with the latest software remains to be solved. In these cases, the various commercial means of physical recovery and recycling of as many materials as possible must be brought into play.

Many of the author's research findings on optimizing electronics recycling published over the past 20 years have not advanced that much. As separation and recovery processes improve, progress tends to

be offset by more complex products using more diverse materials. As noted in other chapters of this book, fundamental changes in the materials used to make future electronics will also be needed to achieve new levels of sustainability.

Carbon-based electronics may be one way to get there. Reducing the complexity of electronics through carbon technology is showing great promise for improved recycling. This 2020 study demonstrated "… complete recyclability of all materials in printed, all-carbon electronics using paper substrates, semiconducting carbon https://arxiv.org/abs/2009.10225 nanotubes, conducting graphene, and insulating crystalline nanocellulose." (See Williams, Nicholas X., George Bullard, Nathaniel Brooke, Michael J. Therien, and Aaron D. Franklin. "Fully printed, all-carbon, recyclable electronics." arXiv preprint arXiv:2009.10225 (2020) https://arxiv.org/abs/2009.10225).

Another study has reported that "Transistors that are printed on paper substrates using all-carbon inks can be completely recycled, providing a potential route to helping solve the problem of electronic waste." (See B. Lee and S. Chung, "Printed carbon electronics get recycled," Nat. Electron., vol. 4, no. 4, pp. 241–242, Apr. 2021, doi:10.1038/s41928-021-00578-w.)

These advances are not limited to individual graphene transistors. Using many transistors to make integrated circuits is a natural progression toward fully organic electronics. These researchers printed single-crystalline thin films of p- and n-type organic semiconductors, graphite-based carbon electrodes/wiring, and polymeric dielectrics/substrates.

"These all-carbon-based complementary integrated circuits possess excellent element traceability, thus mitigating the potential environmental impacts throughout the device's life cycle. Consequently, this advancement represents a significant step toward addressing the global environmental challenges associated with e-waste." (See K. Watanabe et al., "All-Carbon-Based Complementary Integrated Circuits,"

Adv. Mater. Technol., vol. 9, no. 5, Mar. 2024, Art. no. 2301673, doi:10.1002/admt.202301673.)

This work continues to progress.

This section concludes with another example, “Duke engineers advance carbon-based, recyclable electronics,” posted by the Advanced Carbon Council in November 2025 (see https://advancedcarbonscouncil.org/blogpost/2151389/514983/Duke-engineers-advance-carbon-based-recyclable-electronics).

This work highlighted three advantages.

“First, the carbon-based materials are fully recyclable. Printed transistors can be removed from their substrate, and their constituent components can be reused to create new inks…”

“Second, using a single printing system reduces the energy requirements typically associated with multiple fabrication tools.”

“Finally, the technology removes reliance on vacuum-based processes, which are associated with significant greenhouse gas emissions.”

Fortunately, making progress toward sustainable products already has intelligent assistance available in the form of engineering tools and standards, to which we turn next.

For Further Reading

R. L. Franz, “Optimizing portable product recycling through reverse supply chain technology,” *IEEE International Symposium on Electronics and the Environment,* May 6–9, 2002, San Francisco, CA, pp. 274–279. (https://ieeexplore.ieee.org/document/1003279)

Key Takeaways

“Recycle” is a valid path to follow, but the electronics road is imperfect at best, and recycling does not necessarily equate with being highly recyclable. The complexity of materials and the presence of substances of concern are factors that remain to be overcome with today’s set of

electronics hardware, and new materials in electronics are needed to break through the barriers of so much complexity and so little possibility of circularity; these might ideally emulate the composition of the "hardware" of carbon-based life itself. Both personal responsibility for initiating proper treatment, as well as institutional efforts, can be employed to make recyclability and circularity the best it can be today, while regulations that drive circular product requirements complement volunteer industry programs to ensure and measure progress.

Finally, to understand electronics, you need to know physics and math. To understand sustainable electronics, you also need to know about chemistry.

In the next chapter, you will see how standards and engineering tools can be used to enable more sustainable products by design.

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6. Tools and Technical Standards

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This chapter is about using what is already well known from a scientific perspective that has been written into consensus-based standards that can help guide sustainable innovation. Some of the old truths we take for granted appear obvious because they are, well, so true day in and day out. Research and development without common standards, terminology, and metrics would leave industry without practical guidance to enable things to operate reliably and be used successfully in practical applications. Along the way, a new circular electronics schematic diagram using standard symbols is introduced.

What you will take away from this chapter

- Standards for Life Cycle Assessment
- Environmentally conscious design standards and engineering tools
- Standardized ways to extend product life through reliability and maintainability
- Standards for recycling operations
- Example of how standards help develop new technologies: Conductive textiles

Why Standards Are Important

Eco-design, sustainability, and the circular economy may seem new, but recognized standards are already in place to help you meet these

important challenges. In so doing, given the bigger picture of sustainability and the environment of our world, we should expect to run into and learn how to align with some old truths.

As an example of the utility of standards often taken for granted, when you travel around a given country, you expect that a power outlet will work the same in any location. This expectation is enabled by the work of standards in the background. In the United States, the main supply voltage for many devices is 120 VAC, with connections provided by the NEMA-1-15 two-prong and NEMA 5-15 three-prong types of mating connectors. These have been standardized by the National Electrical Manufacturers Association (www.nema.org). Other international locations have their own applicable standards, so you may need a "standard" power adapter there.

The world of standards and standards organizations is quite large in its own right. Beyond the NEMA standard, several others are very important to electronics and sustainability, including the following four.

- **International Organization for Standardization (ISO)**: These standards cover a broad range of subjects, with the notable exception of electrotechnical coverage.
- **International Electrotechnical Commission (IEC)**: The subject matter here is specifically focused on electrical and electronics.

Both are international, meaning that individual country standards organizations comprise the membership and voting bodies for their standards and other guidance documents. Standards so developed and released may be co-branded by both organizations jointly.

- **IPC**: The IPC standards for material declaration have already been discussed in great detail. IPC (originally called the Institute for Printed Circuits, having expanded its scope later on to the Institute for Interconnecting and Packaging Electronic Circuits) is currently the Global Electronics Association (electronics.org). Its standards retain the brand of IPC.
- **Institute of Electrical and Electronics Engineers** (IEEE): Its subject matter is exactly as suggested in the name, although closely

related technologies like optics and software are also within its purview. Besides publishing standards, publications and events are hosted by IEEE. (See https://en.wikipedia.org/wiki/Electronic_symbol.) Other more regional or country-based standards also exist, which may have a dynamic relationship with other standards. (They are mentioned as needed.)

One of the facts of many standards is that they are not always free to the public. This is a fact of life since these organizations sustain their ongoing existence through the sale of their documents. However, it does mean that, in most cases, a direct link in this book to a standard you can read for free may simply not be possible.

What you will learn in the next section

- The standards that can help guide you to optimizing the overall product life cycle from initial manufacturing to end-of-life treatment
- How to achieve longer product life cycles to improve sustainability and reduce wasted resources
- How product life cycles can be made more closed-loop

A Standard Circular Circuit

Figure 6-1 is a new yet simple and standardized way to show the electronics life cycle in the native symbolism of electronics: a schematic diagram. There are several schematic circuit symbol standards, notably IEC 60617: Graphical Symbols for Diagrams (see https://std.iec.ch/iec60617). Only a few symbols are needed here.

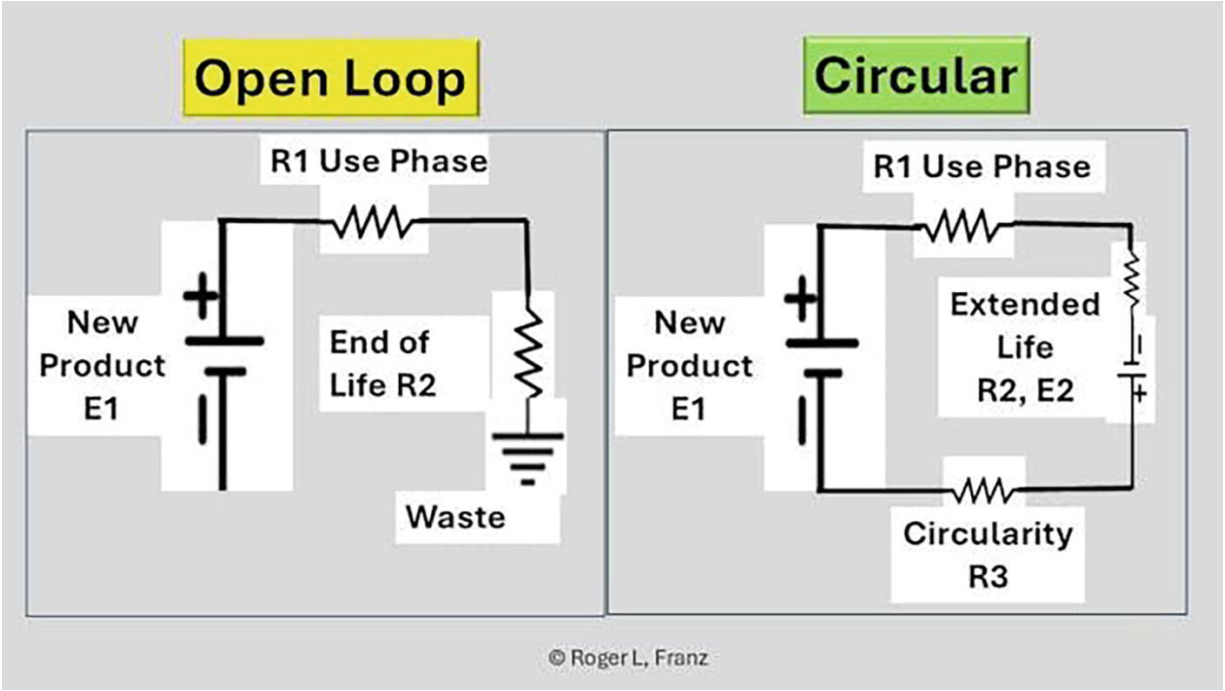


Figure 6-1 A new schematic diagram for circular electronics

Rather than showing the typical circling arrow for the product life cycle once again, Figure 6-1 shows a concept schematic diagram for our theme. Here we show an "open circuit" on the left and a "closed circuit" on the right. It is a basic electrical representation of what this book is all about.

It is not intended to be a working circuit. Rather, it is more of an analogy that operates as follows:

- E1, the symbol of a battery or power source, represents the initial embodiment of energy and materials in the new product. By extension, E1 may also stand for all other life cycle impacts besides energy, such as environmental impacts on water, land, and air quality.
- The next connection is to a resistor, a common symbol for the opposition to electrical flow, or some kind of load to be operated. The Operation Phase shown by R1 is not literally a resistor component but is intended to be a generally lossy representation of the product in service.
- The Open Loop circuit on the left simply goes to ground, identified as waste; in other words, probably landfill.

- The Circular loop on the right, on the other hand, has a complete circuit through some other operational load, then returns to the source. It is a simple closed loop, circular, electrical circuit.

Closing the material flows includes the use of recycled content and reused parts.

Durability extensions include such measures as improving reliability and maintenance, enabling repair, providing updates and upgrades, refurbishing and reuse.

Following the use phase and before end of life, the next sequence represented by R2 and E2 stands for maintenance, spare parts, refurbishment, remanufacturing, and so on, which extend the product life while contributing some initial material losses and need for incremental energy.

Finally, the last leg through R3 represents a closed loop back to the next new product.

Contrast this with the open-loop figure. Starting with the same E1 going through product life losses through the same R1, the flow then goes directly to ground. In other words, no closed loop exists at all, and the product's end-of-life waste may literally end up in the ground.

Figure 6-1 will hopefully shed new light on the circular pictures so commonly repeated in the context of sustainable electronics.

Tools for Life Cycle Assessment

As introduced in Chapter 5, LCA most often uses intelligent software to help collect the data, calculate impacts from the available models, and output the data for further analysis or publication. This brief section is not intended to be a buyer's guide, and these markets change rather rapidly, but mention of these available LCA tools is made here for the reader's consideration. Some are free or essentially so, while others may carry various levels of licensing requirements for enterprise-level use. Software of this type is most often used for formal LCA studies.

- **SimaPro** (https://simapro.com/)

- **Sphera LCA** (formerly GaBi) (https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/)
- **openLCA** (www.openlca.org/)
- **One Click LCA** (https://oneclicklca.com/)
- **Umberto (iPoint Systems)** (www.ipoint-systems.com/software/umberto/)
- **Ecochain** Mobius/Helix (https://ecochain.com/)

Standards for Life Cycle Assessment and Product Declarations

A note about the availability of standards from organizations like IEC, ISO, and IPC: The released standards themselves must be purchased, so this book is able to provide links to the organizations but no direct link to the standards mentioned.

Continuing with LCA from the last chapter, several standards apply. Three of the most often referenced ones are in the ISO 14000 series.

- **ISO 14040** – *Environmental management – Life cycle assessment – Principles and framework*
- **ISO 14044** – *Environmental management – Life cycle assessment – Requirements and guidelines*
- **ISO 14046** – *Environmental management – Water footprint – Principles, requirements and guidelines*

Without getting into all the details, let it be said that performing an LCA that is in conformance with these standards, or can even be certified by a qualified independent body, is not to be taken lightly. Understandably, various simplified methods or software-enabled shortcuts may be used with good intent and valid results.

Since LCA may be the basis of data for reporting and product labeling, the following standards may be relevant depending on the

type of reporting. They all provide guidelines for verifiable, transparent reporting of the environmental aspects of products, but beyond that, they do not provide guidance for how to improve what is reported.

- **ISO 14020** – *Environmental labels and declarations – General principles*
- **ISO 14021** – *Environmental labels and declarations – Self-declared environmental claims (Type II environmental labeling)*
- **ISO 14024** – *Environmental labels and declarations – Type I environmental labeling – Principles and procedures*
- **ISO 14025** – *Environmental labels and declarations – Type III environmental declarations – Principles and procedures*

Standards to Guide Product Design

As a participant for some time in the IEC TC111 Technical Committee on Environmental Standardization, the author can vouch for the dedication that this group of industry and academic volunteers demonstrates in the development of standards for environmental and sustainability issues in electrotechnical products. Of note is ongoing work to develop new standards and revise older ones in the areas of eco-design, restricted substances, recycling, reuse, and sustainability evaluation.

Of prime importance is to employ a mindset of being environmentally conscious in product design in the first place.

IEC 62430: Environmentally Conscious Design For Electrical and Electronic Products

Here we get into the more technical aspects of product design. IEC 62430 provides guidance for minimizing the adverse environmental impact of devices throughout their life cycle. The publication defines environmentally conscious design for all electrical and electronic products, for instance, which materials are used, the quantity of energy consumed to make them, as well as their rate of “recyclability.”

Some additional insights about IEC 62430 are covered in the author's article "Grasping for Sustainability? Standards Come to the Rescue!" in *USNC Currents* (Summer 2023, pp. 5–10). This article is publicly available at https://share.ansi.org/Shared%20Documents/Standards%20Activities/International%20Standardization/IEC/USNC%20Current/News%20and%20Notes/Vol.%2018%20No.%202%20Summer%202023.pdf.

Some major steps detailed in IEC 62430 provide standardized guidance to organizations serious about environmentally conscious design.

Many of the requirements are about governance and record-keeping in product design for a manufacturing enterprise. While a product engineer would no doubt comply with a company's other processes and procedures, the IEC Standard provides several more specific directions to a product engineer on what to consider from an awareness perspective, listed in section 4 of the standard.

These two key points support environmentally conscious design (ECD):

- Life cycle thinking
- ECD as a policy of the organization

Additional actions supporting life cycle thinking include

- Begin with an objective to reduce environmental impact
- Identify and consider design options across the product's life cycle
- Do so early in design and development

Performing a formal design review is another best practice. Many companies already incorporate design reviews at one or more stages of new product development, but IEC 62430 spells it out with respect to the environmental impact considerations.

Design Review Actions – IEC 62430 section 5.5.2

- Establish and maintain a process to review and further reduce environmental impacts of products.

- Conduct such reviews at planned intervals to ensure coverage of all life cycle states.
- Be able to account for changes in both internal and external factors, including stakeholder requirements.
- Improvement actions shall be implemented if environmental objectives have not been met.

IEC 62430 also provides this useful table of specific areas where Design for Sustainability can engage.

Each Design Focus Area contains specific environmental improvement strategies. These may be summarized under each area as follows; text following the bold titles is commented based on the author's experience and is not necessarily defined as such in the IEC 62430 Standard.

- **Design for material sourcing**: It is generally reported that some 80% or so of a product carbon footprint is related to material selection. Trade-offs between material choices that can satisfy product performance and reliability requirements, and at the same time conserve the use of materials and their environmental impact are covered here.
- **Design for manufacturing**: Use of resources, not the least of which are related to energy consumption during production and infrastructure of the factories themselves, figure into this section.
- **Design for transport and distribution**: The distance and mode of transportation have clear impacts and opportunities for optimization.
- **Design for use (including installation and maintenance)**: The environmental scope of the product may be defined as raw materials through manufacturing only (cradle-to-gate). But if the use phase is considered, it may have significant impacts on the overall product life cycle. For example, fuel- or electricity-using products may have a significant use phase impact; not so much for a passive product such as furniture.

- **Design for end of life**: Again, depending on the environmental scope being considered, the recovery of original materials to re-enter the circular economy is considered here. Ideally, if some portions of a larger product can be redeployed for additional service in the field, that can reduce or at least delay loss of resources. Recycling as a material back into the circular economy is the next choice, which is being done today with examples like single-use food containers made of recyclable plastics such as PET, or to some degree with electronic products where copper and precious metals can be recovered and remade into new products to reduce the impact of mining new metals.

More on the Ecosystem of Environmental Standards

Standards are inter-related even though published by different standards organizations. For example, in the IEC 62430 Bibliography we find these related ISO standards:

- **ISO 14001:2015**: *Environmental management system – Requirements with guidance for use*
- **ISO 14006:2011**: *Environmental management systems – Guidelines for incorporating eco-design*
- **ISO 14020**: *Environmental labels and declarations – General principles*
- **ISO 14040:2006**: *Environmental management – Life cycle assessment – Principles and framework*
- **ISO 14006**: *Guideline for incorporating eco-design*, also calls into play certain actions by product designers. One of its first sections is similar to the IEC standard, such as this section: 0.3 Life cycle thinking and trade-offs. Further details of ISO 14006 are not reviewed here.

You can readily see the interaction of standards among eco-design, management systems, and environment. As standards continue to

change and adapt to the latest developments, they can reach their own end of life. Given the dynamic nature of standards, ISO/TR 14062 is now withdrawn from the IEC-ISO joint standard, leaving IEC 62430 on the upward left leg. Also note that standards are not forever but are subject to periodic revisions and updates to keep them current and incorporate the latest best practices.

Related standards may also be found on a regional basis; for example, EN45560: Method to achieve circular designs of products. This standard (EN = Europäische Norm) is filled with useful guidance on relevant topics like reuse, which is the preferred method to extend product life. Also covered are other means of lifetime extension: durability, reliability, maintenance, repair, refurbishing, reconditioning, remanufacturing, and finally, recycling. Besides organizational targets, specific processes and examples are included.

To close this section, one more important group of standards should be mentioned: ASTM (The American Society for Testing and Materials), now an international organization. ASTM standards are of particular value when proving out basic performance of new materials, like how bioplastics behave compared to traditional plastics. Examples include ASTM D7075-04 – Standard Practice for Evaluating and Reporting Environmental Performance of Biobased Products and ASTM D6400-04 Standard Specification for Compostable Plastics. (See www.ieee.org/.)

Standards for Extended Product Life

This section covers key technical standards on how to reduce the environmental impact of materials.

- **IEC Technical Specification 63428**: Guidance on material circulation considerations in environmentally conscious design

  IEC TS 63428:2024 describes principles and provides guidance on how to embed material circularity aspects into the design and development of products.

This includes making efficient use of materials and closing material flows in design and production, extending the lifetime of products through increased durability and enabling parts and materials to be reused or recycled at end-of-life.

Beyond establishing the basic mindset, other standards provide guidance on how to design more sustainable products. Second are some ways to use well-established methods to engineer reliability and durability, and plan for maintenance and repair to help extend product life. Third, when our goods inevitably become electronics scrap, standards can help set goals to achieve a closed-loop material cycle and help reduce reliance on newly mined or manufactured materials.

Improvements in material recyclability, parts reuse, and remanufacturing are possible through measures such as design for disassembly, separability of materials, choice of materials, traceability of materials, and durability of parts."—International Electrotechnical Commission (see https://webstore.iec.ch/en/publication/70549).

While much of this guidance applies to mechanical design and product-level packaging, some progress in "greener" components and circuit boards is also being made. For example, is there a low-halogen mold compound that minimizes toxins during end-of-life processing, and new circuit board laminates based on natural materials like lignin from trees?

Being aware of possible end-of-life scenarios during new product design can also be valuable. Standards can help define and measure how electronic materials are recycled today. Take this European standard, for example.

- **EN 50625-1:2014**. Collection, logistics and treatment requirements for WEEE – Part 1: General treatment requirements.

  This standard applies to the treatment of WEEE until end-of-waste status is fulfilled, or until the WEEE is prepared for reuse, recycled, recovered, or disposed of. This standard addresses all operators involved in the treatment, including related handling,

sorting, and storage of WEEE. As you can see from the version date of 2014, this standard has some history, and standards may become withdrawn and either sunset or be replaced, as is the case here. A later document is drafted and in progress at the time of this writing.

- **prEN 50625-1:2025.** Collection, logistics, and treatment requirements for WEEE – Part 1: General treatment requirements.

  prEN 50625-1:2025 is *proposed* and up for balloting for 12 weeks as of October 17, 2025. This update does not change the message that the later revision still provides important guidance to the electronics industry. Standards are dynamic and may evolve as technology and market conditions require to remain current.

- **CLC/TS 50625-5:2017**. Collection, logistics, and treatment requirements for WEEE - Part 5: Specification for the final treatment of WEEE fractions - Copper and precious metal

  The main intent of this Technical Specification is to specify minimum % recovery targets by weight for copper and precious metals. Practically speaking, because these metals have economic value and can be refined again and returned for almost endless cycles of new products, they are prime examples of circularity as we know it today.

  Before the recycling process begins, the "reuse" phase is important to extend product life, or in other words, make the circle of product life longer. Next, we move to guidance on product maintenance and repair parts, which are some of the other benefits of eco-product design to extend product life without complete replacement. This is because up-front provisions for spare parts or modules help keep the product in usable form with less environmental impact than requiring a complete replacement.

  Two of the important concepts in this section are *reliability* and *maintainability.* Note that the titles of the references do not specifically mention environment, circularity, or sustainability, which seems to have been somewhat overlooked by environmental advocates, but these standards and methods actually fit very well with the theme of sustainability by increasing the length of product

life, thus reducing constant demand for new resources. After the first document listed, the rest are publicly available. The age of some of them proves our point that much of what seems to be new is, in fact, not new at all if we had just been paying attention to product longevity rather than having a mindset of throw-away or rapid product obsolescence.

- **IEC 61709:2017** Electric components – Reliability: Reference conditions for failure rates and stress models for conversion

  This 373-page standard gives additional detailed guidance on the use of failure rate data for reliability prediction of electric components used in equipment. EC 61709:2017 gives guidance on the use of failure rate data for reliability prediction of electric components used in equipment. T Reference conditions are the typical values of stresses that are observed by components in the majority of applications. Reference conditions are useful since they provide a known standard basis from which failure rates can be modified to account for differences in environment from the environments taken as reference conditions. Each user can use the reference conditions defined in this document or use their own. When failure rates stated at reference conditions are used, it allows realistic reliability predictions to be made in the early design phase.
- **Guidelines to Understanding Reliability Prediction: European Power Supply Manufacturers Association** (European Power Supply Manufacturers Association. "Guidelines to understanding reliability prediction." Revision October 13, 2004)

  This document is a guide to reliability concepts like failure rate, mean time to failure (MTTF), mean time between failures (MTBF), and mean time to repair (MTTR). Reliability prediction is probably well known to those working in the military, aerospace, and related industries with critical high-reliability requirements. Automotive suppliers may be required to meet their own customer-specific standards. The application of these methods to more sustainable electronics products is to extend the length or arc of the life cycle

rather than short-circuit the product to a less sustainable phase, not the least of which would be scrap.

While it is not being suggested that all kinds of products need to be, or even should be, designed for High-Reliability performance, many of the same principles and methods are widely applicable even though published as MIL Standards. Nor does this introduction attempt to duplicate any of the many excellent textbooks or courses on reliability engineering or the requirements to become a Certified Reliability Engineer, etc. But the lessons taught by these documents are free to those who want to use them in a lean approach suitable for your company's products.

Updated software tools to complement the written standard methods for evaluating reliability and maintainability may also be found, for example, from companies like Relyence (https://relyence.com) and HBK (Hottinger, Brüel & Kjær) (www.hbkworld.com/en/solutions/applications/reliability).

- **MIL-HDBK-217F**: Reliability Prediction of Electronic Equipment (https://s3vi.ndc.nasa.gov/ssri-kb/static/resources/MIL-HDBK-217F-Notice2.pdf)

  One of the main results of this prediction by component type is that parts most likely to fail should be understood and mitigated as early as possible. Since failure rates multiply together, product complexity can only increase the likelihood of failure. Concepts like MTTF and MTBF lead to statistical distributions, calculations, and predictions.

  Longer-lived products prevent the proliferation of new products from replacing them.
- **MIL-STD-202G**: Test Method Standard Electronic and Electrical Component Parts (https://nepp.nasa.gov/DocUploads/1F6AB74B-4517-4AD0-A34813268E75B8EB/MIL-STD-202.pdf)

  Products will not always have the luxury of sitting on a shelf in unchanging surroundings. For example, temperature variations, even

just transporting the product to the market, are real. The same is true for relative humidity.

A design team can tailor a test plan for accelerated life testing that corresponds to the expected end-use environment of a given product. These test conditions may include stresses like high and low temperature, thermal shock, humidity, and moisture, or, if appropriate, environments like sand, dust, or salt spray. On the mechanical side, vibration and mechanical shock, as well as simulated shipping of the product, may be appropriate.

Manufacturers of outdoor products like automobiles and trucks know these conditions well. Even consumer products may benefit in the marketplace from the assurance of reliability in the field through this type of testing.

This standard is used as a guideline for product testing to ensure the environmental durability of all kinds of products, thus extending the useful life of the product.

- **MIL-STD-1629A**: Procedures for Performing a Failure Mode, Effects and Criticality Analysis (https://extapps.ksc.nasa.gov/Reliability/Documents/milstd1629_FMEA.pdf)

  In this method, consideration is given to how any aspect of a product could fail to perform. Each potential failure is ranked by its likelihood of occurrence and the severity of its effect on product function so that appropriate corrective actions may be taken to eliminate or control the high-risk items. The method can be applied to both design and production.
- **MIL-HBK-472**: Maintainability Prediction (www.dsiintl.com/wp-content/uploads/2017/04/MIL_HDBK_472.pdf)

  A significant advantage of using a maintainability prediction procedure is that it highlights for the designer those areas of poor maintainability which justify product improvement, modification, or a change of design.

Simply put, items like chemical or mechanical parts that may wear out or fail before solid-state electronics, like batteries and rotating components, would wisely be accommodated by designs that accommodate repair or maintenance parts. While this is common sense, it supports product longevity, which is a key principle of sustainability.

Three standards provide useful technical guidance for predicting, testing, and improving the expected life of products before they are placed on the market, including those not intended to be High Reliability.

Practically speaking, another way to extend product life is to repair, refurbish, or remanufacture it. These actions will usually have a smaller environmental footprint than discarding a product and manufacturing a brand-new replacement. Both predictive and desk-level methods have been listed here, along with others that involve physical testing in a laboratory.

The circuit board repair operation is a practical implementation of the more predictive methods of product life extension by repairing or refurbishing the product to extend its service life. It is shown here to highlight a comment often made by electronics recycling companies that the design intent was to discard rather than consider design for repairability. Design for repair and maintainability has unfortunately often been overlooked in the rush to get the latest product features to market.

Finally... Recycling Technology

Ultimately, every product must reach the end of its useful life. Then material recovery and recycling become critical to enable material circularity and reuse in new products, as opposed to ending up as waste.

Within the IEC 62430 framework, there are examples of recyclability for electronic products where copper and precious metals can be recovered and remade into new products to reduce the impact of

mining new metals. (See https://share.ansi.org/Shared Documents/Standards Activities/International Standardization/IEC/USNC Current/News and Notes/Vol. 18 No. 2 Summer 2023.pdf.)

This final material recycling and recovery step is critical to closing the circular economy of all materials, not just metals. Other standards come in to help here as well. Ultimately, both the original product and any spare parts installed to prolong useful life will need to enter the recycling phase to complete the circle.

First, let us look at a series of standards with separate parts dedicated to specific types of equipment:

- **BS EN 50625**: Collection, logistics & treatment requirements for WEEE

WEEE is the acronym for Waste Electrical and Electronic Equipment. This multi-part document contains the following parts, including specific types of equipment:

- Part 1: Collection, logistics & treatment requirements for WEEE. General treatment requirements
- Part 2-1: Collection, logistics & treatment requirements for WEEE. Treatment requirements for lamps
- Part 2-2: Collection, logistics & treatment requirements for WEEE. Treatment requirements for WEEE containing CRTs and flat panel displays
- Part 2-3: Collection, logistics & treatment requirements for WEEE. Treatment requirements for temperature exchange equipment and other WEEE containing VFC and/or VHC
- Part 2-4: Collection, logistics & treatment requirements for WEEE. Treatment requirements for photovoltaic panels

Attention is called to Part 5 of EN 50625, which directly addresses commonly recyclable metals in electronics, copper, gold, silver, and palladium:

- **EN 50625-Part 5**, now DS/CLC/TS 50625-5:2017: Specification for the final treatment of WEEE fractions – Copper and precious metals

This Technical Specification addresses the processes regarding the recycling of copper and/or precious metals contained in WEEE and fractions of WEEE. In addition to copper, the precious metals in scope of the standard are gold, silver, and palladium. A table on Metal Yield specifies input to recycling of 100% and a minimum recovery yield of 90% by weight for these four metals: copper, gold, silver, and palladium.

A metal smelter is a place where many metals are recycled to be reused again, so this is a very critical step in a circular economy. These operations may combine the processing of raw ore with end-of-life goods, sometimes called urban mining due to relatively valuable amounts of precious and related metals in electrotechnical products.

Standards also exist for different recovery streams from electronics.

Due to the nature of electrotechnical products, conductors like metals and insulators such as polymers are ubiquitous. Improving the common technologies and standards that can be applied to material recovery and recycling is a challenge to continuously improve material circularity.

Components that require stable configurations of metals, plastics, and other materials like ceramics are currently processed by shredding and sorting operations. Then, ultimately, the metals are sent to a smelter for recovery along with newly mined ore.

Consideration to at least be able to release a circuit board and components from a mechanical housing and keep larger mechanical housings limited to as few different materials as possible is probably still the most common-sense guidance that can be given today.

Summary of This Section

Table 6-1 shows a list of documents and their applicability to design and materials selection, reliability and maintainability, or end-of-life recovery and recycling.

Table 6-1 Summary of Standards for Longer Life Products

This chapter introduced the existing standards that are available to support and improve the circularity of materials, the point being that we do not have to start from scratch but just need a reminder of the standards already in place and ready to be followed. Applying these standards in practice will need to be joined with the broader business, economic, social, and political environments around the world to drive continued progress. In simple terms, we need to make the circle of product life bigger to use fewer resources.

Considerable progress has already been made. Let it become standard practice and continue!

(See https://share.ansi.org/Shared Documents/Standards Activities/International Standardization/IEC/USNC Current/News and Notes/Vol. 18 No. 1 Winter 2023.pdf.)

Other Considerations Beyond the Hardware

These are three of the key UN Sustainability Goals most applicable to electronic goods, as numbered there.

#7 Affordable and clean energy
#12 Responsible consumption and production
#13 Climate action

The first two should be apparent in their relevance to electrically operated hardware.

The UN goal on Climate Action is largely in response to studies published by the Intergovernmental Panel on Climate Change, the most recent report of which was released in 2025.

All of this is not new, even though recently the heat has been turned up. It was back in 1987 that the UN Brundtland Commission Report first defined global sustainability.

In addition, ISO 14067 is one of the key standards focusing on carbon footprint reporting:

- **ISO 14067:2018**: *Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.*
- **ISO 14067** metrics are used to compare scores of final products, using formal LCA techniques that the individual product design engineer may or may not directly use, since LCA requires specific expertise.

To round out the suite of environmental standards, Material Declarations are important not only for resource management but also for the management and control of regulated substances and other substances of concern that could be harmful to life and the environment. The IEC 62430 Bibliography lists this Standard:

- **IEC 62474**: *Material declaration for products of and for the electrotechnical industry*.

  IEC 62474 also supports a list (published as a database) of declarable substances.

  IEC 62474 is a business-to-business reporting standard to ensure ease of information sharing and consistency across the supply chain. It specifies a means to report substances and materials in a machine-readable XML (Extensible Markup Language) format. IEC 62474 is accompanied by a list of reportable substances that may be found in electrical and electronic products, the IEC 62474 database on material declaration.

To round out the Standards ecosystem, we have already discussed in detail the IPC-1752A Materials Declaration Management standard (www.ipc.org/TOC/IPC-1752A-wAm1-2.pdf). Its purpose is the same as IEC 62474 and uses an XML format. Interaction between IPC and IEC has ensured that the two standards are very similar, although not quite identical and not interchangeable. Both rely on software implementation.

More “Bigger Picture” Perspectives

Design for Sustainability is now a mainstream requirement coming from governments, regulators, and customers. Much of this is new to mechanical or electrical product designers, although some engineering programs are increasingly adding courses on environmental aspects to traditional engineering curricula. It is probably fair to say that Design for Environment may be new to most engineers who have graduated from traditional engineering school programs, depending on location. This is not entirely the case since European universities have been developing strong environmental product engineering programs for some time now.

> “Inevitably, mechanical engineers must also be sustainability engineers.”
> —Michael Johnson, ASME (www.asme.org/topics-resources/content/workforce-blog-engineering-a-more-sustainable-future)

Electrical and electronic engineering has always been the domain of power management and will continue to remain so, more than ever now, with electrification supplanting the burning of fossil fuels. Standards related to electrical power efficiency have largely been the domain of the IEEE as well as extending to the IEEE 1680 series on environmental assessment of electronic products.

It should be clear from even these brief descriptions of the available standards; the sustainability practitioner does not have to begin alone or invent everything along the way. Standards such as these provide a common basis for not only current commerce but for building a better future based on solid foundations.

This chapter has summarized some of the specific ways that IEC 62430 and related standards can be applied today to the pressing needs of climate action. These actions can readily be extended to reduce other environmental impacts as well, for example, emissions to

air and water, and reduction in the use of toxic substances. All are impacted by the reach and volume of electronics today.

Consideration of eco-design standards may be built into simpler aids like checklists for design reviews and goals formally specified in product requirements documents. Legislation like the European Green Deal and Circular Economy Action Plan will move such actions from conformance to voluntary standards to compliance with legal requirements. The number of requests we see growing across the supply chain for sustainable reporting will continue to increase.

Standards are critical to our sustainable future. In the next section, we tie several of the voluntary standards to mandatory regulations and begin to apply them more specifically to electronic hardware.

The Quest for Standardized, Sustainable Components

Standards may be voluntary, but regulations are enforced.

The European Commission published a comprehensive Sustainable Products Regulation governing eco-design requirements. Here is what you need to know at the component level about its eight basic provisions.

What you will learn in this section

- The eight general provisions
- How implementing eco-design brings both similarities and differences between products and components
- How you can use available tools and methods to help assess and quantify some of the more elusive "-abilities": *dura-, relia-, reusa-, upgrada-, repaira-, maintaina-, remanufactura-*, and *recyla-*, not to mention *sustaina-*

These are all tied together in Figure 6-2 as spokes of the wheel of sustainability.

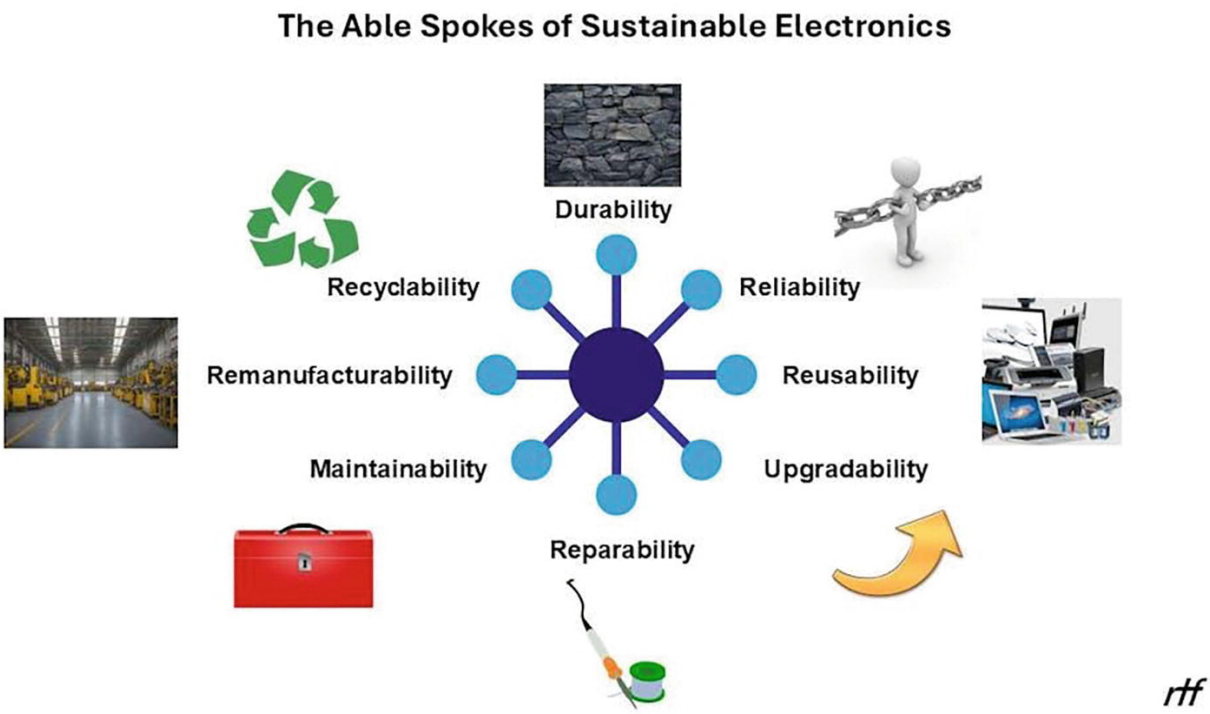


Figure 6-2 Spokes of the Wheel of Sustainability

The basis for the following discussion is this introductory section of the EU's Sustainable Products Regulation, which has already been introduced. We repeat the points here with emphasis added by the author.

"Chapter I - General provisions contains these 8 points to consider, with 5 of them addressing produce life extension and recycling.

Article 1 Subject matter and scope

(a) **product durability and reliability;**

(b) **product reusability;**

(c) **product upgradability, reparability, maintenance, and refurbishment;**

(d) the presence of substances of concern in products;

(e) product energy and resource efficiency;

(f) **recycled content in products;**

(g) **product remanufacturing and recycling;**

(h) products' carbon and environmental footprints"

Before we can begin to answer, "what makes a sustainable component," a brief definition is in order.

What Is a Component?

This Directive is about *products*. Typical electronic products are made of individual parts, also called *components*. A *component part* is generally understood to be

> "An independent physical body that contains the realization of an electronic property or properties and cannot be practicably reduced or subdivided without destroying its function." (See A. Butterfield and J. Szymanski, A Dictionary of Electronics and Electrical Engineering. Oxford University Press, 2018. Available at https://webstore.ansi.org/standards/ipc/ipc89812025.)

The difference between the nature of a *component* and a higher-level assembly of a *product* is immediately apparent. *The inability of a component to be reduced or subdivided without its destruction* is important to remember. Each of the following sections considers components as well as products.

In the context of sustainability regarding components, a commonly recognized Life Cycle Inventory database from ecoinvent (see https://v371.ecoquery.ecoinvent.org/Account/LogOn?ReturnUrl=%2fAccount%2fChangeAccountSettings) lists the following familiar components that have environmental impact data, as mentioned in the opening pages of this book. Most of the general types

of components come in different flavors, which are all constructed differently and use different starting materials.

- Capacitors: Electrolytic, tantalum, film, SMT
- Resistors: Metal film, wire wound, SMD, potentiometer
- Inductors: Wire wound, RF, choke, multilayer SMT
- Transformers: High and low voltage
- Diodes: Glass, SMT, through-hole, LED
- Transistors: IGBT, SMT, big, small
- ICs: Logic, memory, wafer
- Printed wiring boards: Through-hole, SMT, Pb, Pb-free, used, scrap
- Magnets: Permanent for motors
- Connectors: Cable w/o plug, bus, peripheral, plug for computer/network/printer

Missing at the present time in this database are mechanical items like hardware (bolts, nuts, washers), commonly used metal alloys like brass (although individual metals have data), and most engineering plastics. The other components listed have at least a representative environmental impact model.

To help achieve more sustainable *products*, more sustainable *components* are key. Next, we go through the requirements one by one, addressing both sides of the challenge. These are numbered according to the preceding list.

(a) Durability and reliability

For end equipment to be durable and reliable, its component parts must have at least the same properties or better. Durability in the sense of actual use cases places demands mostly on the end equipment and physical packaging.

Mobile products, for example, should be designed to handle some mechanical shock from accidental dropping. Shipping product packaging must withstand transport, including mechanical shock and vibration. Temperature extremes, thermal shock, and humidity resistance apply to both components and packaging, while protection

from other environmental conditions like sand, dust, salt spray, and even vacuum and radiation may need to be considered in equipment design and component selection alike. (See https://extapps.ksc.nasa.gov/Reliability/Documents/milstd1629_FMEA.pdf and www.electronicdesign.com/techxchange/article/55236595/get-started-on-more-sustainable-electronic-design.)

Durability testing may be specified to include protocols similar to those available in standards like MIL-STD-202, which can be tailored as appropriate to the end market of a given product, whether high reliability or not.

Reliability (see https://asq.org/quality-resources/reliability) can be more precisely defined and measured as a combination of aspects, including

- Probability: The likelihood of mission success
- Intended function: For example, to light, cut, rotate, or heat
- Satisfactory: Perform according to a specification, with an acceptable degree of compliance
- Specific period of time: Minutes, days, months, or number of cycles
- Specified conditions: For example, temperature, speed, or pressure

Reliability can also be predicted and quantified according to standard methods like MIL-HDBK-217F. The heart of this method is based on data for components and parts count, including some 22 familiar component types plus a miscellaneous parts category.

(b) Reusability

Examples of reusable components have been around for some time. They include the ability to unplug a part like a vacuum tube or a specific frequency crystal, or what had become common practice just a few years ago to remove and reuse memory chips from end-of-life computers.

If an external power supply is considered to be a component (some would argue it is a module), a very good example of reusability is AC-DC USB chargers and cables using USB connectors. Given some competition in the USB connector choice, with USB-C appearing to be taking over, these supplies are highly reusable across many equipment types.

Complete and functional consumer products may also become reusable, for example, by donating them so that other parties may continue to use what you no longer want or need.

(c) Upgradability, reparability, maintenance, and refurbishment

This item leads to many possibilities. The close relationship between components and end equipment for these aspects of eco-design is clear.

Upgradability could apply to either hardware or software. In the former case, if part of the end product is compatible with a newer or more advanced component or a module, the life of the equipment could be extended. The item being removed for replacement nonetheless needs to be treated according to best practices for circular material recovery.

For software, upgrades are common practice, but it requires that the hardware be compatible with the new code. This dead end has happened to the author when trying to upgrade a PC to the latest operating system, but alas, the hardware was dated and could not handle it.

Repair, maintenance, and refurbishment are all very similar terms that address extending the life of nonfunctional equipment. Repair implies some action is needed to restore the equipment to working order, while refurbishment describes rebuilding larger parts of the equipment for the same purpose to extend product life. The option to use brand-new or used components may exist as well. Automobile owners will experience one or more of these activities at some point with tires, batteries, fluids, and so on.

The key to all of this involves some smaller part of the end equipment being fixed so that the entire equipment does not become end-of-life, but it remains in service.

As with reliability prediction, standard methods of maintainability prediction exist, too; for example, MIL-HDBK-472 (see www.dsiintl.com/wp-content/uploads/2017/04/MIL_HDBK_472.pdf).

This standard begins with a certain amount of "philosophy" (that exact term is actually used several times) followed by guidance to perform analysis and develop a maintainability plan suitable for the equipment under consideration.

Other formal methods, often grouped together as Reliability, Availability, Maintainability, and Safety (RAMS) analysis, can be applied to those aspects of circularity for a comprehensive approach. Software tools make RAMS accessible, for example, in commercially available solutions combining Reliability, Availability, Maintainability and Safety, and more.

Some precautions for equipment repair at the component level need to be taken during the application of solder heat for moisture-sensitive devices to prevent explosive "popcorning." Refer to the well-established guidance found in IPC J-STD-033D-2018, Handling, Packing, Shipping and Use of Moisture, Reflow, and Process Sensitive Devices (see https://webstore.ansi.org/standards/ipc/ipcstd033d2018).

(d) The presence of substances of concern

Thanks to the reality of several regulations, electronics companies have ready access to lists of such substances:

- EU's RoHS Directive restricts heavy metals, brominated flame retardants, and several phthalate plasticizers.
- EU's REACH Candidate List controls over 250 substances of very high concern.

- California's Proposition 65 is yet another list of chemicals, based on risk of exposure.

(See https://std.iec.ch/iec62474.)

Bottom line: Be aware of these substances and design them out of your products. This is sometimes easier said than done, but clearly the intent of this item is to keep hazardous substances from being spread around the world in high-volume electronic products.

(e) Energy and resource efficiency

These two aspects may often seem to be unrelated, since the former applies to energy use during manufacturing and transport of the product, followed by energy required during the use phase and treatment at end-of-life. While energy may also be considered a resource, the intent of it is more commonly focused on the material resources used in the component or product.

No single, clear definition of resource efficiency is widely accepted, but it may include such things as:

- The availability of the element or material.
- Ability to be recycled and returned to the stream of commerce.
- Recycled content (see the next section).

Manufacturing resource efficiency may be enhanced by:

- Using captive regrind of thermoplastics.
- Reducing part volume and weight.
- Reducing or eliminating factory waste.
- Recycling what little unused assembly materials remain.

Some of these approaches may be applicable to components, especially the trend toward miniaturization that inherently reduces the use of materials.

Component energy efficiency examples include low contact resistance and low energy modes of power-supply ICs and other active components. Product energy efficiency may involve approaches like low standby modes enabled by smart circuits. Overall design strategies

to use less energy could result in recognition of, for example, the ratings promoted for consumer appliances by Energy Star and EPEAT for other electronic products.

(f) Recycled content

Using recycled engineering-grade thermoplastics for component applications is unfortunately very rare at this time. Packaging for shipment using recycled consumer plastic or paper content is a positive exception.

Recycled content in many metals, on the other hand, is easily achievable. That is because copper and its alloys, once collected from end-of-life products, can be refined in metal smelters and continually help reduce the environmental burden of freshly mined ore. Steel is another very common example. Recycled metal specifications for electronic goods (see https://ec.europa.eu/info/node/123797) include very relevant recycling streams for copper and precious metals like circuit boards.

End products are more likely to accommodate larger amounts of recycled plastic, for instance, in housings intentionally sourced from recycling streams. In some products other than large appliances and vehicles, most of the metal content of end products comes from their components and circuit boards.

(g) Remanufacturing and recycling

Remanufacturing applies mainly to products, such as replacing defective components and reassembling the product as it was manufactured in the first place.

Recycling can be optimized for products if some of the larger mechanical parts, like housings made of separable, single materials, are sent for recycling and the product is remanufactured with new housings.

It is somewhat more difficult to say how most of the components listed earlier could practically and economically be remanufactured. A

basic requirement of a component is that it be an entity with functionality all by itself, almost always requiring some electrical conductor (metal or filled, conductive material) or semiconductor (silicon, gallium arsenide, etc.) and insulator (resin or ceramic).

The state of the art today for component recycling generally involves size reduction and shredding to recover the metals and some fillers such as glass that may be recoverable. Creating sustainable components that resolve these basic conflicting requirements should be a challenge for today's students and applied in tomorrow's sustainable component industries. We have proposed that more carbon-based components may help solve some of this puzzle.

(h) Carbon and environmental footprints

The output calculations of a Life Cycle Assessment may include one or more environmental footprint metrics. One of the current hot metrics is carbon footprint, which may include the carbon footprint of raw materials and fabrication, including component and/or product manufacturing and transportation, to put on the market. These steps comprise a cradle-to-gate scope.

Adding the use phase and end-of-life recovery phases widens the scope considerably for energy-using products like electronics (not to mention those like vehicles again that consume fuel of one kind or another) to a truly circular cradle-to-grave, or better yet, cradle-to-cradle circular life. Reducing the carbon footprint of components may include the following:

- Reduced footprint material selection.
- Using locally sourced materials.
- More energy-efficient manufacturing.
- Factories that use renewable energy rather than fossil fuels.

When New Minerals Need to Be Mined

Ideally, all materials would have a closed-loop circular path, but in reality, some new minerals will continue to need to be extracted from the Earth. The IRMA Standard (Initiative for Responsible Mining

Assurance) (see https://responsiblemining.net/what-we-do/standard/irma-mining-standard/) is a method to evaluate best practices when mining is required. It covers aspects of water, air, biodiversity, waste, and social responsibility (human rights, labor, community engagement, Indigenous Peoples' consent, and legacy planning), with over 400 requirements for transparent, independent auditing. In summary, these are its four core principles:

- Business Integrity
- Social Responsibility
- Environmental Responsibility
- Planning for Positive Legacies

Following the guidance of IRMA and the like should be standard practice for more sustainable mining operations.

Summary of This Section on Standards

The challenges of eco-design for electronic products lay before us, with many of the diverse and demanding "abilities" yet to be fully realized in most components. Novel approaches to redesign and rethink components that were designed in the vacuum tube era and adapted to through-hole, then surface-mount solid-state assembly are still largely in need of making a more sustainable and circular reality. Only with awareness and innovation will change be possible. Luckily, engineering has many capable and deeply technical support tools to help, as discussed in the next section. (See www.electronicdesign.com/technologies/industrial/article/55306319/the-quest-for-sustainable-components.)

Engineering Tools to Design for Sustainability

Design for Sustainability is now a mainstream requirement from governments, regulators, and customers. Next, we summarize some current trends in the area of PLM tools to support rapid engineering

assessment of environmental footprint among the many engineering choices. Engineering and science-based tools to quickly guide hardware engineers toward material selection and product configuration choices with reduced environmental footprint are critical to our future.

A full Life Cycle Assessment (LCA) according to the ISO 14000 series of standards and others with a focus on carbon footprint, like the Greenhouse Gas Protocol (https://ghgprotocol.org/), requires a dedicated LCA tool and Life Cycle Inventory (LCI) database. These tools, of which several have been available for years, require considerable subject matter expertise not generally provided in mechanical or electrical engineering schools.

Here we report an end user's perspective on some of the tools now available for product designers who may not have significant environmental engineering expertise. The data is based on publicly available information from the software providers' online literature, which reveals quite a diversity of approaches. No further testing or validation has been conducted. Mention of the companies shall not be considered to be an endorsement by the author, who is not employed by or otherwise compensated by any of them. More information may be found in their direct links provided.

Autodesk

Autodesk has announced the availability of a plugin to Makersite (https://makersite.io/). Their approach is not unlike other large software companies that align with one or more third parties offering complementary services.

"Sustainability begins at the heart of the product: its design phase. With the new Autodesk Fusion 360 plugin powered by Makersite, Designers will now have the power to combine Makersite's environmental impact and cost data with Autodesk Fusion 360's product design data."

"The new Autodesk Fusion 360 add-on powered by Makersite features:

- The ability to allow designers to have Makersite instantly calculate the environmental and cost impacts of their design by sending a simple BOM at the push of a button
- Gives Fusion 360 users access to over 300 materials, cost, and sustainability insights, based on the used structure, materials, and weight
- Provides enhanced data sets on over 50 decision criteria such as compliance, risk, health, and safety in real-time."

In this implementation, we see the use of two other trends: artificial intelligence and digital twins.

"Makersite uses artificial intelligence and graph technology to build Digital Twins of manufactured products. This approach enables teams to measure impacts and collaboratively identify optimal mitigation strategies and new sourcing opportunities in real-time and make better products faster. Engineers and product teams can develop more compliant, safer, cost-effective, and environmentally friendly products faster, and get results up to 50x faster than traditional methods."

In addition to ecoinvent (https://ecoinvent.org/the-ecoinvent-database/), which is a widely used LCI database, the Makersite approach is to use multiple databases.

"Makersite's Data Foundation (https://makersite.io/makersite-data-foundation/) is the solution to the challenges manufacturers face when sourcing components and complying with sustainability and regulatory commitments. Our product knowledge graph, the largest in the world, brings together data from over 140 sources, providing access to the largest product and supply chain database. Our databases cover a wide range of materials and substances, allowing you to model products from various sectors, including automotive, electronics, packaging, and food. We monitor 40+ regulations and include major LCA databases, including ecoinvent and IDEA. With information on 36,000+ industrial processes, 600,000+ environmental impacts, and 100,000+ materials and properties in one system."

Dassault Systèmes

Another approach is to create a direct pipeline from design tools, specifically the 3DEXPERIENCE platform, to the ecoinvent LCI database.

In 2022, Dassault Systèmes announced the launch of "Sustainable Innovation Intelligence" (see www.3ds.com/sustainability/lifecycle-assessment), its Life Cycle Assessment solution that enables companies to minimize the environmental impacts of the products, materials and processes they create and help drive the circular economy. Fully embedded in Dassault Systèmes' 3DEXPERIENCE platform and covering the entire value chain, the cloud-based solution uniquely integrates the ecoinvent database on the impacts of more than 18,000 industrial and agricultural processes into virtual design, product development, manufacturing engineering, operations and logistics."

In the announcement, "Sustainable Innovation Intelligence" further explains the leverage of the digital or virtual twin approach: "Embedding LCA within the virtual twin—as Dassault Systèmes' Sustainable Innovation Intelligence solution does—introduces a host of new possibilities for a net-zero economy. To consistently deliver accurate insights, Dassault Systèmes has partnered with ecoinvent, an environmental database provider with a diverse repository of high-quality lifecycle information."

"Equipped with complete LCA data and a unique virtual twin offering on the 3DEXPERIENCE platform, companies are better poised to innovate towards circular product lifecycles, gain a competitive edge and win the climate fight."

A recorded Dassault Systèmes webinar that goes into much more detail about the system operations and its video may be accessed at https://events.3ds.com/builtin-lifecycle-assessment-sustainable-development.

Additional information from ecoinvent (https://ecoinvent.org/) includes the following: "The ecoinvent Database enables users to gain a deeper understanding of the environmental impacts of their products and services. It is a repository

covering a diverse range of sectors on a global and regional level. It currently contains more than 18,000 activities, otherwise referred to as 'datasets', modeling human activities or processes. ecoinvent datasets contain information on the industrial or agricultural process they model, measuring the natural resources withdrawn from the environment, the emissions released to the water, soil and air, the products demanded from other processes (electricity), and of course, the products, co-products and wastes produced."

This is the same database that may also be used when performing a full LCA using dedicated LCA tools.

Dassault had early versions of the same concept more than ten years ago in the SolidWorks system, where CAD and the PLM database were linked through a user interface to LCA software and database, using a Mass-Material-Process association. Tools of this kind continue to improve and be deployed for more general engineering use. (See www.echa.europa.eu/candidate-list-table.)

PTC

The approach to sustainability here is to address material use reduction head-on through the use of Creo's advanced CAD tools. Using generative design, the mechanical engineer can remove material and weight while keeping the mechanical properties needed for performance and reliability.

Engineering productivity and time-to-market may benefit from AI-driven generative design, with sustainability being supported as well. well.

This approach has been confirmed in practice, notably by their customer Cummins.

"With sustainable products and practices among the highest business priorities, Creo is providing significant gains within the Cummins design program. Cummins has realized that applying generative design to any conventionally designed part typically reduces the material used by 10 to 15 percent. This approach reduces the

environmental footprint and the cost and weight for any given component."

"Cummins knows that in the world of power solutions, getting to market faster while optimizing environmental sustainability across operations, manufacturing, and service often traces back to sound design practices. After design engineers describe the engineering and operations requirements for the task, Creo offers a suite of design and simulation tools to aid the development of the design concept. This process enables their design engineers to develop and iterate on design concepts more efficiently, avoiding the typical back-and-forth work that occurs between the designer and analyst and allowing for a much more effective use of these critical resources. Furthermore, this allows them to explore possibilities they previously would have never been able to explore because of time restraints."

"Leveraging Creo Generative Topology Optimization, Creo Simulate, and Creo Simulation Live (CSL), Cummins is designing and testing digital prototypes to understand how they will perform in a real-world engine system. CSL provides real-time feedback on design decisions, so designers can iterate more quickly and generate more options, which saves designers an incredible amount of time. Each time a change is made, the change is analyzed in seconds as part of the typical workflow —all without leaving the CAD environment for greater efficiency."

The case study can be found at https://www.ptc.com/en/case-studies/cummins-optimizes-product-designs.

A partnership between PTC and Makersite may further use their combined capability in the engineering/CAD/PLM space to enable product engineering capability for LCA calculations.

Siemens Digital Industries Software

Here we see a somewhat different strategy to pair up carbon footprints with cost estimation.

"With our Teamcenter Product Cost Management solution, you can assess product costs and carbon footprint at the same time. You can

also get a holistic idea of how you can model, design, and produce without compromising emission goals," writes Emilia Maier in a blog on Siemens' website (see https://blogs.sw.siemens.com/teamcenter/achieve-the-dual-mission-of-product-cost-and-carbon-emission-savings/).

Within the PLM system, CO_2-equivalent attributes are displayed in a product BOM page for easy viewing of raw materials, purchased components, and a roll-up to the BOM parent.

"An integrated approach for calculating product CO2e footprint and cost along the entire value chain enables companies to make trade-off decisions between driving down CO2e emissions, reducing product costs, and addressing customer value demands."

"By creating a visible link between product cost and product carbon footprint, companies can identify the most important levers that will yield the greatest savings and implement those first. They can analyze the impact as a trade-off between the product carbon footprint, profit margin, and customer value."

"Companies can do all sorts of product carbon footprint calculations and what-if simulations in the product development phase, looking at the different levers to evaluate trade-offs and take the right decisions."

In addition to managing carbon footprint, reducing the use of substances of concern is another key to reducing environmental footprint. This aspect is also claimed to be integrated into the Siemens approach.

"A sustainability framework that is built into the lifecycle of your products will support the highly sought-after environmental compliance objectives. In addition, the framework allows you to phase out non-sustainable or restricted substances from products and design new and innovative "green" ones."

"Environmental compliance and product sustainability solutions help you control and trace the material makeup of your products down to the substance level. You can limit the use of hazardous substances in

your products and reduce the risk of non-compliance with regulatory directives such as REACH, RoHS, and Conflict Minerals."

In summary, one sees here the merging of engineering tools to manage carbon footprints and other sustainable goals like materials management with product cost.

Summary of Engineering Tools Section

It is probably fair to say that the best approach, much less the optimum approach for your particular products, markets, and customers, has yet to fully play out. At least we already see some very good choices developing, including strategies as diverse as

- linking cost and carbon footprint together
- use of advanced design and simulation tools to reduce mechanical part weight and material use
- making calls from the engineer's workbench to one or more life cycle databases and even other data sources
- use of AI and virtual (or digital) twin to present choices between multiple options and multiple stages of a product's life cycle

We hope that whatever approach your own investigation leads you to will help us all to reach our common goal of a sustainable world.

One alternative to the use of rigid or flexible circuit boards based on synthetic polymers is the use of textiles that may offer some sustainability advantages for next-generation products. The importance of standards to guide innovation is clear in this example.

E-Textiles

Printed electronics on flexible substrates are at the heart of electronic devices prevalent in the fields of wearable monitoring devices, interactive consoles for entertainment and communication, solar cells, RFID tags and antennas for inventory tracking, OLED display screens, and lighting devices. This trend fits well with our theme of flexible, organic electronics for the future.

Textile is a ubiquitous material and a flexible substrate for fabricating printed electronics. Printed electronics on textiles is an additional layer of functionality integrated into this ubiquitous material present in our apparel, upholstery, and accessories.

The goal of the IPC-8952 standard is to establish specific requirements for the design of printed electronic applications (design details, materials, test requirements, mechanical properties, physical properties, thermal management) on textile as a substrate. The standard also establishes the specifications for methodologies of component mounting and interconnecting structures on coated or treated textile substrates. It aims to introduce a common design language and guidelines for use between user and supplier for any given e-textiles with printed electronics.

While standards exist for flexible printed electronics, they do not consider the variations brought in by coated or treated textiles that are otherwise not seen in a standard flexible substrate. These variations include four-way stretchability, surface roughness, breathability, effects of moisture, coefficient of thermal expansion (CTE), edge effects due to textile manufacturing, and finishing processes introducing conductive textiles.

This connection between e-textiles and sustainability may at first seem unlikely. However, as we begin to reveal more and more in the remaining chapters, the most interdisciplinary and "out of the box" approaches may offer the best hope of avoiding the same old environmental dead ends over and over. This bright light is illuminated at the juncture of fashion and technology; one such activity is the WEAR Sustain initiative. This project, which was funded by the European Union's Horizon 2020 R&D initiative, facilitated **W**earable Technologists to **E**ngage with **A**rtists for **R**esponsible Innovation. As stated, WEAR Sustain "Aims to engage wearable technology stakeholders to work more closely with designers and artists across Europe, to shift the development of the EU wearables and e-textiles industries towards a more sustainable and ethical approach." (See

www.digitalspaces.info/_files/ugd/a498eb_2325ee1eb45c4e739f1c4f8e12cb53a0.pdf.)

The potential of practical applications is wide open with such an interdisciplinary approach.

> "Smart textiles have gained great interest from academia and industries alike, spanning interdisciplinary efforts from materials science, electrical engineering, art, design, and computer science. While recent innovation has been promising, unmet needs between the commercial and academic sectors are pronounced in this field, especially for electronic-based textiles, or e-textiles." (See R. R. Ruckdashe *et al., "Smart E-Textiles: Overview of Components and Outlook*," *Sensors,* vol. 22, no. 16, p. 6055, Aug. 2022, *doi:10.3390/s22166055*. Available at https://pmc.ncbi.nlm.nih.gov/articles/PMC9416033/.)

Going back to early printed circuit boards, there have been three generations of substrate materials as follows, showing that textile or various forms of woven support are not new to circuit boards at all.

1. First generation rigid boards—commonly containing a textile or glass weave
2. Textile with devices embedded in them
3. "Fully" textile electronics with electronics not only attached to a surface but part of the interface between, for example, computer and human, for example, for sensing, monitoring energy harvesting, thermal comfort and even interactive drug release.

We leave these exciting possibilities for the moment and return to our theme of technical standards. Developing standards for the rapidly expanding e-textile industry has become more vital than ever. This

section describes in some depth the story behind a relatively new standard for conductive textiles.

Electronic product designers rely on standards for device interoperability, design reuse, quality, lower product-development costs, and increased competitiveness on a level playing field of global collaboration. (See www.ptc.com/en/blogs/corporate/ptc-makersite-accelerate-sustainable-product-development.) Even non-technical users of electronic goods benefit as well, probably without thinking about it. Unless, for example, in their new computer purchase, they see Wi-Fi specified as conforming to IEEE 802.11. Some 1,300 IEEE standards are at work in the devices and functions you are most familiar with.

Within the area of printed-circuit technology, IPC standards provide comprehensive coverage with more than 300 standards, including both electronic design and manufacturing. PC, now called electronics.org, is a global trade association dedicated to furthering the competitive excellence and financial success of its members, who are participants in the electronics industry.

The e-Textile Standards

In this section, we report on standard activities for e-textiles. These materials have been known by various names: ultra-flexible circuits, printed electronics, functional fabrics, technical textiles, wearable technology, smart fabric, smart textiles, and so forth.

This is a list of the IPC standards for conductive textiles (e-textiles).

- **IPC-8911**: Requirements for Conductive Yarns for E-Textiles Applications
- **IPC-8981**: Quality and Reliability of E-Textile Wearables
- **IPC-8921A**: Requirements for Woven and Knitted Electronic Textiles (E-Textiles) Integrated with Conductive Fibers, Conductive Yarns and/or Wires
- **IPC-8952**: Design Standard for Printed Electronics on Coated or Treated Textiles and E-Textiles

- **IPC-8971**: Requirements for Electrical Testing of Printed Electronics E-Textiles (www.electronics.org/e-textiles)
- **IPC-8921-2019**: Requirements for Woven and Knitted Electronics Textiles (E-Textiles) Integrated with Conductive Fibers, Conductive Yarns and/or Wires

IPC-8921 establishes classifications and designations for e-textiles integrated with e-fibers, e-yarns, and e-wires, and standardizes key characteristics, durability testing, and industry test methods. Key characteristics include electrical resistance, electromagnetic immunity, thermal conductivity, coefficient of thermal expansion (CTE), specific heat capacity, thermal shock resistance, outgassing, T_g, and melting point.

IPC-8921 includes 20 new terms and definitions for e-textiles and quality assurance provisions, and test frequency. This standard is the first baseline compilation that merges the textile industry and electronic performance attributes in one document. When used as a benchmark of e-textile performance, e-textile products can be analyzed and compared for use in any application. Development expectations and outcomes may be shared between user and seller for transparency.

A publicly available preview shows the Table of Contents of the complete standard document. Sections on Scope and Applicable Documents, General Requirements are followed by Key Characteristics Durability, Quality Assurance Provisions, and Packaging. The published standard is available at the IPC Webstore.

But this standard was only the beginning. These are some related standards of interest.

- **IPC-8911-2025**: Requirements for Conductive Yarns for E-Textiles Applications

  This standard identifies categories and establishes a designation system and qualification/quality conformance requirements and test methods for conductive yarns used in e-textiles. The standard enables suppliers of conductive yarns to demonstrate their products' performance against real-world processing and end-use

environments, leveraging eight IPC Test Methods developed specifically for conductive yarns."

Developed by the IPC Conductive Yarns for E-Textiles Test Methods Task Group, IPC-8911 defines key yarn categories, introduces a standardized designation system, and includes qualification and conformance requirements tailored to conductive yarns. The standard is supported by eight new IPC-TM-650 Test Methods, designed to evaluate performance characteristics such as conductivity, mechanical durability, and resistance to environmental and chemical exposures."

- **IPC 8952-2023**: *Design Standard for Printed Electronics on Coated or Treated Textiles and E-Textiles*

  The IPC-8952 standard establishes specific requirements for the design of printed electronic applications and their forms of component mounting and interconnecting structures on coated or treated textile substrates. Textile substrate, as pertains to the IPC-8952 standard, could be a bare textile or an integrated e-textile (e.g., woven or knitted e-textile). Coated or treated textile substrates, as pertain to the IPC-8952 standard, are textile substrates which have or will have a coating or treatment localized or across the full substrate."

  Printed electronics on flex are at the heart of electronic devices prevalent in the fields of wearable monitoring devices, interactive consoles for entertainment and communication, solar cells, RFID tags and antennas for inventory tracking, OLED display screens, and lighting devices.

  Textile is a ubiquitous material and a flexible substrate for fabricating printed electronics. Printed electronics on textiles is an additional layer of functionality integrated into this ubiquitous material present in our apparel, upholstery, and accessories.

  The goal of the IPC-8952 standard is to establish specific requirements for the design of printed electronic applications (design details, materials, test requirements, mechanical properties, physical properties, thermal management) on textile as a substrate.

The standard also establishes the specifications for methodologies of component mounting and interconnecting structures on coated or treated textile substrates. It aims to introduce a common design language and guidelines for use between user and supplier for any given e-textiles with printed electronics.

While standards exist for flexible printed electronics, they do not consider the variations brought in by coated or treated textiles that are otherwise not seen in a standard flexible substrate. These variations are four-way stretchability, surface roughness, breathability, effects of moisture, coefficient of thermal expansion (CTE), edge effects due to textile manufacturing, and finishing process.

- **IPC-8971-2023**: *Requirements for Electrical Testing of Printed Electronics E-Textiles*

  One of the main functionalities of printed-electronics e-textiles is the electrical function of the circuits in printed electronics. The functionalities related to the printed conductive traces are electrical connectivity, electrical insulation between adjacent printed conductive traces, and leakage current through a given dielectric layer between adjacent printed traces. These originate from their trace width and thickness, the distance between the adjacent traces, and the thickness of the dielectric layer.

  The IPC-8971 standard outlines the rules for determining adjacent printed conductive traces and the type of adjacency using the CAD/CAM drawings of the printed circuit. Based on this determination, the testing requirements are defined using test methodologies such as resistive continuity or isolation, indirect isolation and continuity (by signature comparison of capacitance, RF, impedance), and testing of accessible midpoints. The end-product classifications for electronic devices—Classes 1, 2 and 3—also are considered for defining the test requirements.

  The standard provides guidance on considerations for electrical test setup, test techniques, and test equipment. A template for Test Certificate of Conformance is included along with guidance on

traceability and statistical process control (SPC) for electrical testing operations. The task group has a plan to complete this standard via ballot by summer 2022.

"IPC-8971 is intended to assist in selecting the test equipment, test parameters, test data and fixturing required to perform electrical test(s) on printed electronics on e-textiles. Printed electronics on e-textiles are printed electronics on coated or treated textile substrates. Coatings and treatments may be applied for printability of the textile substrate and/or for performance of the textile substrate or finished printed electronics e-textile (e.g., hydrophobic, water retardance, flame retardance, surface energy). Coatings or treatments may be applied using printing, lamination or other processes." (See https://webstore.ansi.org/standards/ipc/ipc897120 23.)

- **IPC-8981-2025**: Quality and Reliability for E-Textile Wearables

  As the e-textile market continues to grow, comparable quality and reliability standards across the multitude of e-textile applications become a necessity. Thus far, there are no proper e-textile reliability standards, so e-textile manufacturers look at other, related fields where such standards already exist.

  Faced with the unique challenge of combining two worlds—electronics and textiles with often very different materials, properties, and requirements, those standards often fail to meet e-textile-specific needs. This situation resulted in efforts to establish the standard *IPC 8981 Quality and Reliability for E-Textile Wearables*, starting back in 2019 with a survey among industry and research stakeholders.

  "This standard defines classification levels and testing thresholds to assess the reliability of e-textile wearables in their intended end-use environments. It establishes baseline criteria for evaluating durability under mechanical stressors—such as abrasion, flexing, and UV exposure—and environmental conditions including perspiration, washing, water/saltwater, alkalis, and acids. Supported by 14 IPC

Test Methods developed specifically for e-textile products, the standard also provides guidance for identifying affected and critical areas for reliability testing. (See https://webstore.ansi.org/standards/ipc/ipc898120 25 and https://webstore.ansi.org/Standards/IPC/IPC892120 19.)

Wearable textile electronics have become a reality with products like heart monitoring that can be used outside the medical office.

For an account of how these textile-related standards were developed, written by participants in the IPC Standards Committee, see "New IPC Standards Help Engineers Weave Through the World of E-Textiles (see https://electronicdesign.com/21236763).

Graphene materials are also an active subject for developing new standards. As reported by the Advanced Carbons Council (https://advancedcarbonscouncil.org/page/Standard s), standards for this technology are being developed through ISO, ANSI, and ASTM technical standards committees. Some examples include standards for nano-carbon masterbatch formulations for starting materials, and circularity of reclaimed Carbon Fiber (rCF). These all help to promote this exciting new technology with sustainability in mind from the early stages.

Looking to the Future

Flexible electronics in the form of electronic skins is an active area of research that is moving beyond reliance on silicon chips and other rigid components. (See www.science.org/doi/10.1126/science.abn7325 and www.electronicdesign.com/news/products/article/217 96110/dont-underestimate-the-value-of-standards.)

While these approaches are not expected to replace other types of electronic hardware, the absence of the need for silicon may hold some

promise for other products made with fewer materials, at least for applications that are in close communication with the human body.

When e-textile circuitry is combined with flexible components enabled by 2D and 3D nanomaterials like graphene, nanowires, nano coils, and advanced printing techniques, we will see new applications beyond health and fitness sensors now entering the market. As this technology continues to develop, we might expect the evolving body of knowledge to be incorporated into new standards. These new textile electronic materials offer the opportunity to create lighter-weight, personalized products that can help rethink the current approach to electronic hardware and enable them to be more sustainable by design.

Key Takeaways

So far, this book has covered many of the needs and possible solutions to make electronic products more sustainable. It has also covered what is in these products, how to sort out the good from the bad, and how legislation and the need to quantify results have led to standardization and development of scientific and engineering tools. One remaining area is how electronics are powered by electricity in the first place. This brings us to energy efficiency, which is the focus of the next chapter.

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7. Energy

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This chapter begins by discussing the point at which electronic products connect to electricity. Making electricity from sunlight is no longer news, and one can find photovoltaic (PV) arrays on the roofs of houses in your neighborhood, not to mention commercial arrays and other commercial installations like wind turbines across the land. We tend to favor PV since it is more electronic than mechanical, but other means of sustainable electrical generation are also considered.

Plants eat photons of light and store chemical energy. With a source of water and some critical minerals, they grow, bear leaves and seeds to reproduce. When their life is over, they decompose to start anew.

Electronics consume a flow of electrons. Electrical energy has only been tamed and made useful for the past few hundred years thanks to human inventions. With the exception of lightning, electricity can only be made from other sources of energy, whether optical, chemical, or mechanical.

From an energy point of view, our vision of organic electronics still has an energy gap compared to nature. A solar-powered radio is one example of an integrated energy electronic product, but such items are still somewhat of a novelty, and their practical adoption depends on battery technology.

What you will take away from this chapter, by subject

- Energy generation

- Energy efficiency
- Possibilities from negative and nonlinear resistance
- Batteries and magnets
- Data centers and beyond

Generating Electricity

Chemical sources used to generate electricity, whether petroleum, natural gas, coal, biofuel, or even nuclear fission, are based on creating motion that turns a generator. Even a modern nuclear energy plant fundamentally generates steam to create motion just like a steam locomotive. Generators based on naturally produced mechanical motion like wind, ocean, or hydroelectric power can eliminate this first step because they are already in motion.

In all these cases, the generation of electricity is made possible by a few basic principles of electricity itself. Motion between a magnetic field and an inductor generates electricity, according to Faraday's Law of Induction (see https://en.wikipedia.org/wiki/Faraday%27s_law_of_induction). In a related way, the current flowing through any conductor creates a magnetic field. So, motion may become electricity, and electricity can be made into a magnet. The same principles may operate in opposite directions to either generate electricity from motion, or act like a motor that uses electricity to create motion. On a smaller scale, loudspeakers are a familiar example of converting electricity to motion (sound waves), as are microphones that convert sound waves into electricity.

Leaving the complexities of each type of energy generation aside for the moment, there is a very different way to generate electricity that is more like a plant leaf and requires no moving mechanical parts at all: photovoltaics, or solar cells, convert photons of light directly to electricity. The basis of transistors (bipolar type) and diodes is the pn junction, where the underlying material has been selectively doped with tiny amounts of electron-rich and electron-deficient elements to

create the junction and a barrier between them. This barrier may produce light in a light-emitting diode (LED) or operate in reverse to turn light into energy in a photovoltaic cell. With our emphasis on future, sustainable electronics, it should be clear that the future favors this solid-state kind of generator. While naturally produced air and water motion are also sustainable, the other sources based on chemical combustion are not considered to be sustainable.

Photovoltaics

These energy generators have no moving parts and operate totally under the laws of physics, using semiconductor technology to interact with photons of light. (See https://energyeducation.ca/encyclopedia/Photovoltaic_effect.)

The direct conversion of sunlight to electricity has endless potential. In contrast to burning fossil fuels, solid-state generation of electricity during operation causes no carbon dioxide or any other gaseous emissions, and none to water or solid waste. Most likely, the reader of this book does not need to be convinced that renewable, endless energy from the sun is a good thing. But like any solution, there are some concerns to be resolved and more work to be done. For quite some time, it seems likely that fossil fuel energy and renewable energy will need to coexist: "…in the next three decades, two complementary dynamics will occur: a growth in the consumption of fossil fuels and, at the same time, a deepening in policies, technologies, consumption and production of alternative sources of energy; both, in a context of greater energy consumption efficiency." (See D. Londoño-Pulgarin et al., "Fossil or bioenergy? Global fuel market trends," *Renewable and Sustainable Energy Reviews*, vol. 143, p. 110905, June 2021. Available at www.sciencedirect.com/science/article/abs/pii/S1364032121001982.)

The difference between the two sides of "renewable vs. non-renewable" may become less distinct due to increased use of biofuels and organic waste that is chemically recycled either directly to energy

or fuel, while continuing to use traditional fossil fuel facilities and equipment. (See Chapter 5.)

There may not be enough data to comprehensively prove that alternative energy generation like PV is truly sustainable today. But the facts in its favor show how such technology can and will become sustainable very shortly. The absence of toxic atmospheric and water emissions and greenhouse gases during use is a huge positive. The other life cycle phases, from raw materials to manufacturing to end of life, remain to be shown to be truly sustainable. The specifics depend on which PV technology is being used. While silicon has dominated production to date, others are being developed and may become more competitive. The following are the main contenders:

- Silicon-based and its several variations
- Cadmium telluride (CdTe) and cadmium indium gallium selenium (CIGS)
- Perovskite (a type of crystal structure ABX3 where B is often lead, and X is a halogen like chlorine or bromine) (See https://energy.sustainability-directory.com/learn/what-materials-are-commonly-used-in-perovskite-solar-cells/.)
- Quantum dots
- Organic, of multiple types

(See https://energy.sustainability-directory.com/learn/what-materials-are-commonly-used-in-perovskite-solar-cells/ and www.sciencedirect.com/science/article/abs/pii/S0927024816300381.)

Given the electronics history of facing restrictions on lead, cadmium, and halogens, no more will be said of those PV technologies here.

The development of organic photovoltaic (OPV) technology aligns with a general theme of organic electronics introduced in earlier chapters. While it is not expected that this technology will replace

silicon, the ability to be made flexible has advantages for some installations, and over their lifetime will be capable of generating 100 times more energy than it took to manufacture them. (See M. P. Tsang et al., "Life-cycle Assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies," *Solar Energy Materials and Solar Cells*, vol. 156, pp. 37–48, Nov. 2016. Available at www.sciencedirect.com/science/article/abs/pii/S0927024816300381.)

A Life Cycle Assessment of renewable energy will be required to validate the sustainability of any PV technology.

- **Raw material consumption**: What and where are the sources, how limited or diversified are they, and how can they be minimized and directed to easily recoverable materials? How much of the raw material supply has recycled content? This phase also requires evaluation and minimization of any toxic impacts so that the consequences can be avoided prior to mass production.
- **Manufacturing**: Are there any excessive requirements for energy or water, and how can these be mitigated and continuously optimized by the manufacturer?
- **End-of-life material recovery**: This goes hand in hand with the first item since if a material is recyclable, it will be reusable in the circular sense.

The payback time to recover energy equivalent to manufacturing a solar panel in the first place is only 1 to 2 years, which is minor compared to a typical operating life of 25 years (see https://energy.sustainability-directory.com/learn/how-does-tencouraghe-manufacturing-process-of-solar-panels-influence-their-life-cycle-energy-payback-time/).

On the other hand, in the end-of-life recovery phase, some processes are already in place to recover aluminum, copper, silver, silicon, and glass. Improved recovery methods must continue to be perfected and

become capable of mass deployment to handle the inevitable roughly 25-year end-of-life and replacement cycle. (See G. Ansanelli et al., "A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels," A*pplied Energy,* vol. 290, p. 116727 May 15, 2021. Available at www.sciencedirect.com/science/article/abs/pii/S0306261921002440.)

For organic photovoltaics, a comprehensive study of development from 2020 to 2025 provides a solid foundation for LCA-based assessment of strengths and weaknesses. (See K. Kiskira et al., "Life Cycle Assessment of Organic Solar Cells: Structure, Analytical Framework, and Future Product Concepts," *Electronics*, vol. 14, no. 12, p. 2426, Jun. 2025. Available at www.mdpi.com/2079-9292/14/12/2426.)

The author's conclusions from this study align closely with themes we have presented throughout this book. To paraphrase several of their concluding points:

- Raw materials should be non-toxic, abundant, and preferably bioderived. The use of heavy metals should be avoided, and substrates should be recyclable or biodegradable.
- Manufacturing should follow green chemistry principles, such as low-energy, solution-based fabrication, and incorporate design for disassembly.
- End-of-life management of organic solar cells is favorable due to the absence of toxic metals like lead or cadmium. Components can potentially be recovered through mechanical or solvent-based recycling. Where recycling is unfeasible, safe incineration or biodegradable alternatives may be implemented (which the present author might amend to add incineration with energy recovery and chemical recycling).

No doubt the actual installations would still employ conductors like copper, which has been mentioned often in previous chapters.

Large panel locations must not displace farmland where photosynthesis is the first priority. Recently, future-looking countries have deployed PV arrays on rooftops, parking lots, and wasted space on transportation routes and under power lines. These trends should be encouraged.

(See https://link.springer.com/book/10.1007/978-3-319-49875-1 and www.science.org/doi/10.1126/science.adp6027.)

Wind Power

Similarly, the energy payback period for a typical wind generator is 5 to 10 months, with an operational lifetime of 20 to 30 years (see https://energy.sustainability-directory.com/learn/what-is-the-energy-payback-period-for-a-wind-turbine-considering-the-emissions-from-its-construction/).

These moving generators obviously require mechanical parts and gears to produce enough speed and torque from slow wind motion to power an electromagnetic generator. Making these large blades sustainable rather than ending up in a landfill is still an open need. Learning from nature is starting to influence sustainable design. (See L. Mishnaevsky Jr., "A New Concept of Sustainable Wind Turbine Blades: Bio-Inspired Design with Engineered Adhesives," *Biomimetics*, vol. 8, no. 6, p. 448, Sep. 2023. Available at https://pmc.ncbi.nlm.nih.gov/articles/PMC10603827/.)

To close this section on energy generation, we realize that it gets cloudy and dark and the wind dies down. Hence, next we need to consider energy storage, most commonly a chemical battery, although the use of large rotating devices for kinetic energy and various high heat capacity pools, including low-tech methods like piles of gravel, are some other creative examples. Wind energy gets far enough afield from our core topic, except that principles of designing these structures for material efficiency and recyclability apply like any other electronic

product. Existing infrastructure projects like hydroelectric dams are beyond the scope of this book as well, while some interesting methods to create small hydroelectric reservoirs by pumping water up to a holding area, then releasing it to generate the electricity back are interesting. Some even more interesting non-terrestrial sources with energy potential will be mentioned at the end of this chapter.

On a much smaller scale, energy harvesting is a means to extract tiny amounts of electricity from various sources nearby. These may range from mechanical motion to vibration to temperature differences. (See N. Bizon et al., Eds. *Energy Harvesting and Energy Efficiency: Technology, Methods, and Applications*, Springer, 2017).

Another small-scale source called hydrovoltaics extracts energy from moisture. (See R. F. Service, "'Hydrovoltaics' tap energy from ubiquitous moisture: New devices convert raindrops, dripping water, and even humidity into minuscule currents," *Science,* vol. 384, no. 6691, p. 16, Apr. 4, 2024. Available at www.science.org/doi/10.1126/science.adp6027.)

Enhanced Mineral Demands for Batteries

Among the many types of batteries in use today, including zinc-carbon, alkaline (made so by potassium hydroxide, also containing zinc and manganese dioxide), mercury, lead acid, silver oxide, nickel metal hydride, and nickel-cadmium, the demand for the lithium-ion type is growing rapidly. Lithium cells themselves are of several types (see www.tycorunenergy.com/lithium-battery-types/).

Lithium may be extracted from salty brines and several varieties of hard rocks and clays. (See https://continuous.metalstudy.com/). With the growth of rechargeable batteries for all kinds of electrical and electronic devices, and the rise of electric vehicles, it is critical for this mineral to be sustainably extracted and returned for reuse.

Besides lithium, the batteries may also require other metals like cobalt, nickel, or manganese. Depending on the region in which you live, there may be well-developed recycling and recovery programs to break

down old batteries and recover at least some of the metals for reuse, which is a good start. However, it seems that the recovery of lithium is still lagging behind the other metals.

> "Generally, smelting can recover cobalt and nickel, but it would take additional steps to recover other critical materials like lithium from the residue left behind. Recycling technologies that use leaching may be able to economically recover high amounts of cobalt, nickel, lithium, and manganese and several facilities are in development in the United States." (See www.epa.gov/hw/lithium-ion-battery-recycling.)

- Lithium-ion battery recycling is growing in the EU. (See M. Stephan, "Battery recycling in Europe continues to pick up speed: Recycling capacities of lithium-ion batteries in Europe." Fraunhofer Institute for Systems and Innovation Research, August 7, 2024. Available at www.isi.fraunhofer.de/en/blog/themen/batterie-update/lithium-ionen-batterie-recycling-europa-kapazitaeten-update-2024.html.)

However, exact data on how much lithium itself is being recovered is hard to find. Regulations like Annex XII of the Battery Regulation (see www.greenmemag.com/environment/recycling-spent-batteries-fighting-lithium-and-cobalt-waste-what-changes-with-new-eu-rules-by-december-2025/) that have set targets of 50% of lithium recovery by the end of 2027 and 80% by 2031 will be expected to drive improved lithium recycling. (See www.science.org/content/article/move-over-lithium-sodium-batteries-could-one-day-power-green-economy.)

Another new twist on lithium-ion batteries involves the additional elements of sulfur and selenium, along with the familiar graphene form of carbon. Given the commercial promise of successful batteries, it seems the material creativity will keep moving on. Once again, the need

is to consider how to get these substances back out at the end of battery life and substantiate claims with LCA.

Battery chemistry continues to look at other elements as well. One candidate is the sodium battery. (See R. F. Service, "Move over lithium: Sodium batteries could one day power a green economy," *Science*, Feb. 20 2025. Available at www.science.org/content/article/move-over-lithium-sodium-batteries-could-one-day-power-green-economy.).

Sodium chloride, as in table salt, is plentiful. This is one of many new materials technologies undergoing research.

Various types of processing metals are already available, but the "black mass" of metals that are produced from early steps of lithium-ion battery recycling has remained somewhat of a problem. New approaches like fast electrical heating may be one approach.

Some research has suggested that an efficient, fast-charging battery could be made of basically graphene and aluminum. Should these early developments continue to show promise, this simplified material structure could take some of the pressure off sourcing so many other elements. Our organic friend graphene is involved once again.

Enhanced Mineral Demands for Magnets

Permanent magnets play a significant role in the electrical economy, in generators turning physical motion into electricity, and again on the receiving side, powering fans, pumps and motors including electric vehicles.

The list of energy-critical metals is quite lengthy:

> "…critical metals include some alkaline earth metals like lithium, some first-row transition metals like cobalt, and some p-block metals like tellurium. They also comprise second- and third-row transition metals encompassing the platinum group metals (PGMs)—platinum, palladium, rhodium, ruthenium, iridium, and osmium. Critical metals also include some of the lanthanides

> or rare earth elements (REEs), including lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, and terbium." (See www.cas.org/resources/cas-insights/critical-metals.)

Mining rare earths can be environmentally damaging. Their availability is also subject to geographical and geopolitical constraints. Work is needed to develop more sustainable recovery of these elements; for example, the electrokinetic method that uses electric current to process the leachate from rare earth-rich clays. (See G. Wang et al., "A green and efficient technology to recover rare earth elements from weathering crusts," *Nat. Sustain.*, vol. 6, no. 1, pp. 81–92, Jan. 2023, doi: 10.1038/s41893-022-00989-3. Also see D. Normile, "It is electric! Technique could clean up mining of valuable rare earth elements," Science, Nov. 1, 2022. Available at www.science.org/content/article/it-s-electric-technique-could-clean-mining-valuable-rare-earth-elements.)

Not needing to continue the expansion of the electronic materials set across the entire periodic table is arguably an even more sustainable approach. One possible approach to combating the proliferation of all these metals is to make materials that have similar behavior but are based on more abundant elements.

Using oxides of more common elements is one way to do this.

> "The *ubiquitous element strategy* aims to achieve novel and/or useful functionalities, which have only been found in rare and/or harmful elements, with a restriction in selecting abundant and non-toxic elements for materials design." (See H. Hosono et al., "New functionalities in abundant element oxides: ubiquitous element strategy." Sci. Technol. Adv. Mater, vol. 12, no. 3, p. 034303, Jun. 2011, doi.org/10.1088/1468-6996/12/3/034303).

Researchers are now developing high-performance magnetic materials using earth-abundant elements like iron and nickel to replace

rare earths in permanent magnets. These alternatives include engineered compounds such as iron nitride (FeN) and tetrataenite (FeNi), which offer competitive magnetic properties without the environmental and geopolitical costs of rare earth sourcing.

Another approach is by adding phosphorus to an iron-nickel alloy to make tetrataenite, a powerful magnet found in meteorites that normally takes millions of years to form. (See www.cam.ac.uk/research/news/new-approach-to-cosmic-magnet-manufacturing-could-reduce-reliance-on-rare-earths-in-low-carbon.) This green chemistry breakthrough makes the material in seconds and provides a powerful alternative to rare earths, particularly neodymium magnets.

Alternatives to neodymium that use a much more widely available metal, iron, combined with another very abundant substance, nitrogen, may be a more sustainable approach. (See www.stanfordmagnets.com/iron-nitride-permanent-magnets-a-comprehensive-guide.html.)

Using electronics technology in the form of AI may offer novel ways to find materials to fit a particular need. One such project is DeepMind, a 2025 Nobel Prize winner for AI (see www.nature.com/articles/d41586-025-03713-1). AI has already been applied to search for new batteries, solar cells, and other electronics. Given the wealth of material data that is available, such intelligent technology could help solve a number of problems if the requirements include keeping the complexity and availability of source materials limited and considering how the new material can be recovered later on, not be toxic, and so on, as said often in this book. (See https://digital.sierramagazine.org/publication/?i=829286&p=2&view=issueViewer.)

In summary, it must be said that just “not burning fuel” does not automatically equate to sustainability. The many principles and lessons learned throughout this book need to be understood and taken

seriously by the next generation of Sustainable by Design technologies and businesses.

Given a source of sustainable electricity, next it becomes important to consider how the electronic product consumes what it is provided. Is it efficient or wasteful? Does "off" truly mean off, or is there still wasted energy? What about the billions of rapid on-off switching going on inside a computer chip? To answer these questions, next we will cover:

- Energy efficiency ratings for products
- Standby losses and a success story
- Other forms of leakage current and some new ideas

Energy Efficiency

Energy efficiency is an important consideration in the wider discussion of electrical power. It also has a hidden kink: electronics that are apparently turned off may not be totally turned off and consume standby current. And during operation, a given circuit may not be 100% energy efficient and have internal leakage current losses as well. All these unintended losses may add up to become significant.

Buildings and vehicles are significant consumers of energy but are out of scope for our present focus. Once constructed, the built environment may use both chemical (gas, oil) and electrical energy for things like heating, air conditioning, lighting, and so on. Vehicles may run on chemical fuel or electric batteries. In both cases, the devices and components they may contain are subject to considerations at hand.

Methods to measure energy efficiency and recognition for the levels of energy-efficient operation achieved by different consumer products are represented by these two regional organizations. Many other independent "eco-labels" may also include metrics for energy efficiency.

- **Energy Star** is administered by the EPA and includes different types of electronics and appliances, and even homes and commercial buildings. A listing of Energy Star–rated computers is available to

look up ratings by brand. (See www.energystar.gov/productfinder/product/certified-computers/results.)

- **EU Energy Label** is sponsored by the European Commission and includes not only a comprehensive series of labels for efficiency classes color-coded from A to G but also easy-to-understand information on Ecodesign.

Circuit design and component selection are key to achieving higher efficiency, and like most design trade-offs, some balance between complexity, cost, and benefits is a design choice for a given product. Energy use in operating mode is important, but not to be overlooked is the unintended waste of energy in non-operational or standby modes. This is our next topic.

Success Story: Battery Chargers

Some years ago, the author was working with a team conducting an LCA on mobile phones. While the raw materials and fabrication of the components and the end product, of course, had their own energy impacts, using the battery chargers available at the time turned out to be the biggest energy user over a year of operation. Most prevalent at the time were “linear” power supplies that used a transformer directly connected to house current, followed by the circuitry to convert to DC voltage suitable to charge a battery. These transformer -based power supplies, fondly known as “wall-wart” in some circles, draw current from the mains supply at all times.

From an electrical point of view, it is easy to understand how the transformer, with its iron core that is always drawing current, even if no battery is connected for charging, could add up over time to be very significant, even exceeding the initial energy used to build the product in the first place. One could tell just by feeling their surface that they were warm, with that heat put to no intended use. Of course, one could always unplug the unit entirely, but there was no guarantee that this

would always happen, and many of us left them on a shelf, under desks, and so on, unattended.

Fortunately, electronics technology came to its own rescue with the adoption of much more efficient switching power supplies. These units first chop the line current to a higher frequency and use transistor or integrated circuit switches to turn the unit off when no load from a charging battery is present. These power supplies not only run more efficiently but drastically reduce the standby or "vampire" energy that was wasted with the older designs.

Additional information about the circuitry, commonly known as a switch-mode power supply (SMPS), as well as some history, is available at https://en.wikipedia.org/wiki/Switched-mode_power_supply.

Sustainability Bonus

Along with widespread industry adoption of the more efficient chargers came a bonus in the form of a more universal, common set of connectors. Within the series of USB (Universal Serial Bus) connectors, just a few are now in common use to connect all types of power supplies with all kinds of products needing battery charging or power to operate. Based on standards from the USB Implementers Forum (see https://en.wikipedia.org/wiki/USB_Implementers_Forum), fewer kinds of standard connectors have helped reduce the proliferation of so many unique power supplies with their own unique connectors. Even so, the movement to commonality is not yet complete, even now with some devices using the larger, rectangular USB-A, or one of two USB-B series: mini and micro. One or all of these seem to be converging now on the USB-C oval type. As explained in Chapter 6, standards may be most helpful but may also tend to change and rise or fall in popularity over time. Such is technology. The bonus of common cables and connectors for so many devices running on USB outlets or batteries that need charging is much reduced scrap of unused cables

and connectors. As shown in previous chapters, efficient recovery of the materials in a simple wire is not easy.

Circuit Ideas

This section will by no means be a course on circuit design but rather is intended to bring to light some of the author's work on using components in novel ways to reduce energy consumption and improve energy efficiency. These components fall under the general classification of being nonlinear, meaning that their current-voltage curve is not a straight line like a perfect resistor. This group also includes devices with a region of negative differential resistance, in which the slope of the curve actually reverses before continuing on. This behavior is illustrated in Figure 7-1.

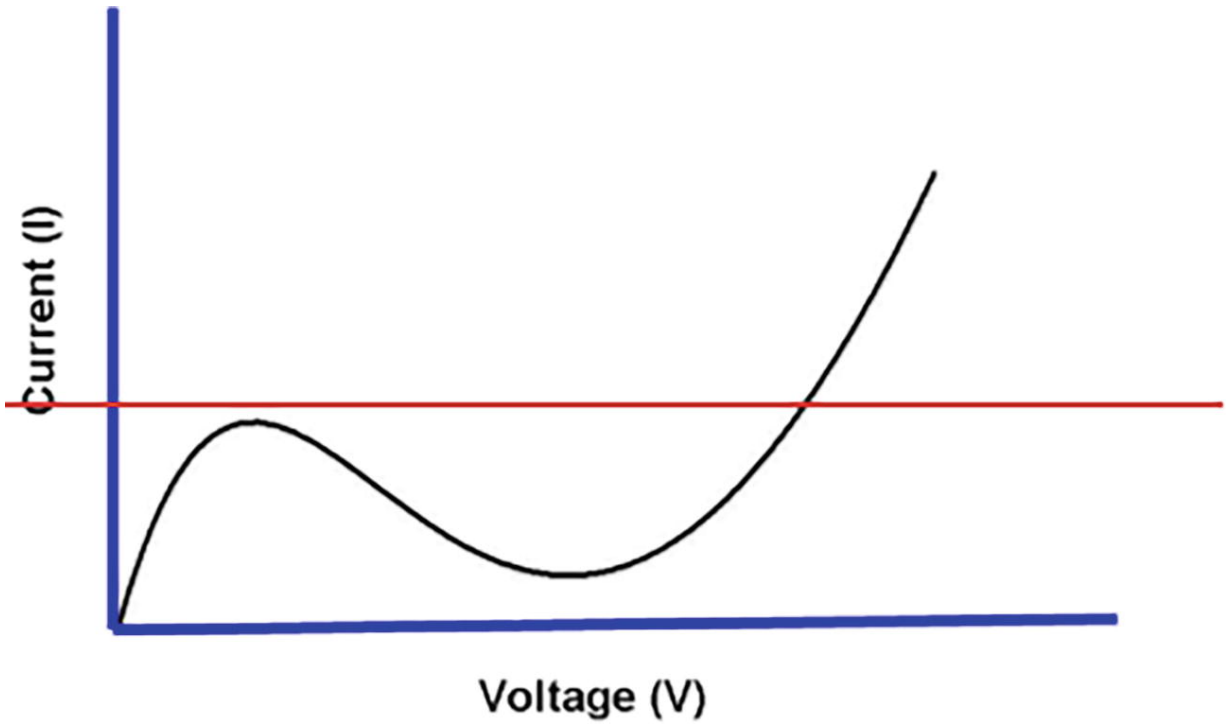


Figure 7-1 Negative differential resistance

A number of nonlinear devices, termed nonohmic for not obeying Ohm's law

Voltage = Resistance times Current

Having a two-terminal structure that is known to exhibit two or more such negative regions in current-voltage behavior may be of considerable value in power management. An ideal device of this type would have no resistance when the surrounding circuit demand is active, making it essentially transparent in operation. However, when current or voltage demands of the circuit fall below some threshold value, this ideal element would turn completely off, thus eliminating any unwanted loss or leakage. Both current-controlled and voltage-controlled devices have been made.

A voltage-controlled threshold switch remains in a state of high resistance until reaching a specific value of applied voltage, above which it becomes highly conducting. This is sometimes called bistability, which refers to two operating regions. These devices typically have only two terminals, which enables them to function as smart switches requiring no additional control lines. The door that is yet unopened is to correctly optimize the materials to achieve a suitable operating curve for each application.

Several types of existing components display negative differential resistance behavior, including the following.

- Tunnel diodes
- Backward diodes
- Gunn diodes
- IMPATT diodes
- Real space transfer devices
- Vapor phase and plasma devices
- Even simple bipolar transistor junctions

The following references catalog over 100 literature references to such devices. Since the materials used to fabricate parts are critical to their sustainability, a wide range of different constructions have been identified for consideration, including

- simple compounds
- multi-material composites
- multilayer structures and junctions

- Ge, Si, and group III-V semiconductors
- group VI elements (chalcogenides)
- transition metals
- organo-metallics

These options may provide some choices to select the most sustainable materials; however, it is suggested here to limit the endless search for more varied materials and concentrate on those where the data has shown the raw material and end-of-life recycling scenarios are the most sustainable.

Carbon-based devices are in the running for next-generation electronics. One example found in nature is the pigment melanin, which behaves as a voltage-activated switch. It is notable that melanin contains the same conjugated single-double bond structure as polyacetylene, which was recognized with a 2000 Nobel Prize as the pioneer organic semiconductor and continues to be researched as a candidate for organic electronics. (See J. McGinness, P. Corry, and P. Proctor, "Amorphous semiconductor switching in melanins," *Science*, vol. 183, pp. 853–855, March 1, 1974.) (Also see A. J. Heeger, A. G. MacDiarmid, and H. Shirakawa, "How can plastic become conductive?" The 2000 Nobel Prize in Chemistry, Information for the Public, Oct. 10, 2000. Available at `http://nobelprize nobelprize.org/chemistry/laureates/2000/ public.html`.)

Polyacetylene serves as another example of a plastic (carbon-based) material crossing into the realm of conductors normally associated with metals.

> "Polyacetylene (PA) is the archetypal conjugated polymer. The seminal discovery of the metallic conductivity of its doped form has triggered a huge surge of interest in conductive polymers and has spawned an exciting area of research on synthetic metals. As a result of rapid advances in the area, we are now on the threshold of a "plastic-electronics era" that previously could only be imagined in science fiction." (See J. W. Y. Lam and B. Z.

Tang, “Functional polyacetylenes,” *Accounts of Chemical Research*, vol. 38, no. 9, pp. 745–754, Sep. 2005, doi: 10.1021/ar040012f.*)*

If polymers can be conductive, is there a need for metals? Recall that the two are traditionally in conflict because it is difficult to separate and process the polymer portion while the metal goes to recovery. This simplified scenario is imperfect due to the small amounts of so many other different metals besides the few that do have a recycling path. Chemical recycling may be an option, and carbon may be its future.

To close out this section, not to be left out are carbon nanotube transistors specifically to suppress leakage current, saving wasted energy. (For example, see W. Gong et al., “Scaling, Leakage Current Suppression, and Simulation of Carbon Nanotube Field-Effect Transistors,” *Nanomaterials*, vol. 15, no. 15, p. 1168, Jul. 2025. Available at www.mdpi.com/2079-4991/15/15/1168.)

More technical details, including many more references to devices with negative differential switching properties, were previously published in the following references.

For Further Reading

R. L. Franz, “Pulling the Plug on Current Drain: Advances in Material Selection for Reducing Standby Leakage,” *IEEE Circuits and Devices Mag*., vol. 20, no. 6, pp. 12–16, Nov./Dec. 2004. (https://ieeexplore.ieee.org/abstract/document/1364770)

R. L. Franz, “Negative Differential Resistance Leads to Some Positive Results,” *Electronic Design,* June 29, 2010. (http://www.electronicdesign.com/archive/negative-differential-resistance-leads-some-positive-results)

R. L. Franz, “Use Nonlinear Devices as Linchpins to Next Generation Design,” *Electronic Design,* June 23, 2010.

(https://www.electronicdesign.com/archive/article/21791385/use-nonlinear-devices-as-linchpins-to-nextgeneration-design)

R. L. Franz, "Nonlinear Devices and Circuits." (https://www.academia.edu/145093395/Nonlinear_Devices_and_Circuits)

R. L. Franz, "Prospects for Energy on Earth." (https://www.academia.edu/145349527/Prospects_for_Energy_on_Earth)

Memristors

Before leaving the topic of components for threshold switching, another completely different kind of component needs to be mentioned: the Memristor.

Memristance offers a solution to the time-based problems of standby current loss and time sharing of electronic data processing resources. How exactly this fourth circuit element will be implemented in practice remains to be seen in the coming few years.

The importance of negative electrical parameters will become clear in a moment. For now, keep in mind the nonlinear current-voltage curve shown in Figure 7-1. Within the curve is a region where the slope becomes negative. This property is used today in many applications like oscillators. Losses related to standby energy, sometimes affectionately known as "vampire energy," could be addressed with nonlinear circuits. In the next sections, we show how nonlinearity can be realized in the next generation of devices.

Consistent with Maxwell's equations of electromagnetism, there exists a fourth electrical element in addition to the familiar component types of resistor, capacitor, and inductor: this fourth electrical component is the memreistor. (See "Memristor—The Missing Circuit Element" at http://cpmt.org/scv/meetings/chua.pdf). Also published in the textbook *Linear and Nonlinear Circuits* by L. O. Chua, C. A. Desoer, and E. S. Kuh (McGraw-Hill, 1987).)

This fourth type of electical behavior has been named memristance. Memristive behavior lies in the relationship between charge and flux, while its present value depends on its past history. If a memristor's voltage or current is known, it behaves like a linear but time-varying resistor.

Until recently, memristance could be simulated only by fairly complex active circuits, but no simple physical circuit element that behaved like a memristor had been reported. A realization of the memristor at the device level has been reported in nano-scale devices, based on TiO2 ("The Missing Memristor Found." Strukov et al., *Nature,* 2008. (www.nature.com/articles/nature06932).

It is expected that developments in this type of new device will enable categories of memories having advantages over CMOS technology that is prevalent today.

This work has just begun, as memristance appeared for the first time as an emerging technology in the International Technology Roadmap for Semiconductors in 2009. But it may be the key to the next level of electronic devices and product performance. Memristive circuits may become good stewards of future energy inputs by operating with low loss, using their ability to change as time-variant demands dictate.

This fourth memristive circuit element completes the functional relationships in addition to resistance, capacitance, and inductance. A graphic showing the relationship between circuit elements may be found in this source (see https://en.wikipedia.org/wiki/Memristor).

Existing electronics technology is amazing enough but has yet to fully realize the utility of memristance to yield new kinds of performance. Improving the energy efficiency of semiconductor memories and switches, while reducing unwanted leakage losses in the off state, continues to be a major technical challenge. Memristor development for computer circuits may only be the beginning of more efficient energy management. Memristance offers a solution to the time-based problems of standby current loss and time sharing of

electronic data processing resources. How exactly this fourth circuit element will be implemented in practice remains to be seen in the coming few years.

Recent work on memristive technologies has highlighted promising applications in data storage, computation, encryption and communications. If not used specifically to manage energy itself, these structures "should improve switching performance and reduce energy consumption" of future digital products. (See M. Lanza et al., "Memristive technologies for data storage, computation, encryption, and radio-frequency communication," *Science*, vol. 376, no. 6597, June 3, 2022. Available at www.science.org/doi/10.1126/science.abj9979.)

Biggest Electronic Product on Earth: Data Centers

Our last product example is a huge one. From cloud computing to artificial intelligence (AI), the computing demands continue to grow. These data centers could have significant environmental impacts.

> "…by 2030, the current rate of AI growth would annually put 24 to 44 million metric tons of carbon dioxide into the atmosphere, the emissions equivalent of adding 5 to 10 million cars to U.S. roadways. It would also drain 731 to 1,125 million cubic meters of water per year…" (See https://news.cornell.edu/stories/2025/11/roadmap-shows-environmental-impact-ai-data-center-boom.)

The number of individual data servers in some of these data centers can range from hundreds to thousands to over a million. Small improvements in energy efficiency and reduction in the need for cooling on an individual box-by-box basis may add up. But will it be enough?

As a digital device operates, some power is consumed, which depends on things like operating voltage, clock frequency, and internal

leakage currents. Clock frequencies continue to rise to meet greater computing power, which has not helped. Since a computer system needs DC power to operate, the power supplies required to convert AC line current to DC will also generate heat. Multiply these heat-generating sources by many thousands to millions to give some idea of why temperature management is a problem, since these measures also require energy. A common-sense observation has been made that data centers should not be located in hot climates where more air conditioning and heat management are required. (See www.tomshardware.com/tech-industry/nearly-7000-of-the-worlds-data-centers-are-built-in-the-wrong-climate.) Whether other, not the least of which are short-term, economic incentives will enable changing current trends remains to be seen.

A coalition led by Food & Water Watch, including national organizations such as Greenpeace USA, Friends of the Earth, the Ohio Environmental Council, Physicians for Social Responsibility, and dozens of regional and state-based groups from all 50 states has noted that the uncontrolled growth of data centers poses "one of the biggest environmental and social threats of our generation." (See www.sciotopost.com/more-than-200-environmental-groups-call-for-national-moratorium-on-new-data-centers-including-ohio/.)

The letter, sent to the US Congress on December 8, 2025, called for a "national moratorium on new data centers until adequate regulations can be enacted to fully protect our communities, our families, our environment and our health from the runaway damage this industry is already inflicting." (See www.foodandwaterwatch.org/wp-content/uploads/2025/12/Org-Letter_-National-Data-Center-Moratorium.pdf.)

Some of the solutions may require a new generation of devices that inherently use less power than current memory technologies. (See www.techbriefs.com/component/content/article/51744

-a-new-microelectronic-device-uses-less-power-than-current-memory-technologies.)

While there is a critical need to reduce electricity and cooling demands for data centers, let us think for a moment outside the box about sources of energy.

Beyond Today

The aging power grid is based on very low frequency (50–60 Hz) alternating current. Frequencies of future interest lie above even radio waves and microwaves, into the optical region of the spectrum and beyond to X-ray and gamma radiation. These frequencies are sent to us by the Sun and are all around us from innumerable sources across the universe. Advances in electronics and optics will soon be able to tap into these boundless energy sources and provide useful electricity to our systems here on Earth. This is our energy future: Earth's magnetic field, the energy of the sun, and all the stars, including other galaxies.

It is well known that the Sun sends something on the order of 1 kW per square meter to Earth. This is the basis of current solar (photovoltaic, wind, ocean, etc.) energy. What if we could harness not only our own Sun more efficiently, but the energy of additional suns as well?

As originally proposed in a paper discussing radio transmission limitations between distant life forms, civilizations may possess varying degrees of ability to harness the energy around them. We might note that the word "harness" itself comes from utilizing the energy of a horse or other animal, while we intentionally open the scope to include any means of capturing energy for any intended use. (See N. Kardashev, "Transmission of information by extraterrestrial civilizations," in *The Quest for Extraterrestrial Life* (University Science Books, 1980) p. 136. Available at http://adsbit.harvard.edu//full/1964SvA.....8..217K/0000219.000.html.)

The energy harnessing classifications of Kardashev are as follows:

- Type I civilization – can harness all energy of their own planet
- Type II – able to harness energy of their own sun
- Type III – harness energy of their own galaxy
- Type IV – tap energy of multiple galaxies, universes

The energies available on Earth and within our solar system and galaxy are estimated as follows:

- Earth 10^17 watts
- Sun 10^26 watts
- Milky Way galaxy 10^37 watts

As of the twenty-first century, we on the planet Earth have achieved only a pre-Type I energy mastery. Based on the preceding figures, we have some 20 orders of magnitude improvement yet to realize.

How can this be done? On such a now-classic proposal is a Dyson sphere. Whether this originated in a paper by the noted physicist, Freeman Dyson (1667–1668), or in a science fiction novel is an interesting controversy. Dyson admitted that he was inspired by the highly acclaimed science fiction novel *Star Maker* (1937) by British author Olaf Stapledon. In *Star Maker*, Stapledon described "a gauze of light traps" surrounding every star in the universe, which "focused the escaping solar energy for intelligent use." (See F. J. Dyson, "Search for Artificial Stellar Sources of Infrared Radiation," *Science*, vol. 131, no. 3414, pp. 1667–1668, Jun. 1960. Also see www.sciencefocus.com/space/dyson-spheres.)

Also called a Dyson swarm, bubble, or shell, constructing such an energy collector could theoretically capture all of Earth's energy needs from the Sun; however, doing so is not without a number of significant complications, which we will not get into here. (See https://science.edu.gr/research/sapappas/Dyson%20Spheres%20Harnessing%20the%20Full%20Power%20of%20a%20Star.pdf.)

But let the inspiration continue.

Energy from the Vacuum (Cheniere Press, 2024) is a collection of theories published by Thomas Beardon in a book of the same name that

picks up where our discussion of differential negative resistors leaves off. In this view, a true negative resistor can be an energy generator, and pages of electronic theories are provided to explain ways to do it. However, it seems that the practical results have either not been as predicted, or they may have actually worked and become shrouded in secrecy because freely extracting the energy from all around us would be opposed to the principle of making a profit from everything.

Thinking on an even more cosmic scale, it has been observed that black holes could be a tremendous source of energy. (See I. Semiz, "Black hole as the ultimate energy source," *American Journal of Physics*, vol. 63, no. 2, pp. 151–156, Feb. 1995, doi: 10.1119/1.17869.)

Whether this will be a practical source of energy or electricity in the near future is uncertain, to say the least. But it serves as another reminder that energy is all around us, and the search for boundless energy will no doubt continue. This seems like a good place to end without running out of energy while leaving room for creativity and innovation.

Key Takeaways

- Electronics, by definition, need electricity to operate.
- Several of the more sustainable forms of energy generation based on solar, wind, and even small local sources were reviewed.
- Equally important to not only portable, cordless devices but also energy storage in the grid are batteries, for which technology and materials are rapidly evolving.
- Data centers, which are the growing trend for cloud computing and AI, could be mass consumers of electricity in their own right, while requiring cooling in the process.
- Some out-of-this-world sources of energy were introduced.

The next chapter discusses group resources, which brings us back to the realm of humans with common interests.

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8. Group Resources

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This chapter is about sustainability group resources. Its intent is to share selected LinkedIn groups and others with common interests in the pursuit of sustainability. The links are organized in these categories, recognizing that there may be significant overlap between them.

What you will take away from this chapter

- Introduction and disclaimers about the groups listed
- Sustainability, chemistry, and industrial ecology
- Recyclers

Introduction and Disclaimers

1. This list is not comprehensive. There are too many groups to list, so if you feel left out, please join the conversation or start a new group.
2. The intent here is not to list companies or groups promoting commercial interests, while the scope is limited to LinkedIn groups, although there are many other fine organizations.
3. While there are some general categories, groups within each one are listed in no order of preference.
4. The author claims no formal rights or endorsement with respect to any of these groups, which maintain their own group governance

any of these groups, which maintain their own group governance and membership rules.

5. A link to each group is provided for convenience, as found on the group's page. Text about each group provided is quoted directly in good faith, from the group page wherever possible. Some are privately listed, so a request must be made to join the group. Other links go directly to the association itself.

Sharing common interests and passions is yet another way we can achieve a better world together.

Sustainability Groups

This first list is on the technical side, ranging from chemistry to engineering to industrial ecology. There may be some overlap with topics like environment, circularity, and material recycling; these distinctions are arbitrary since they are all related. The second list is equally important to fulfill the physical need for recycling.

PLM Green Global Alliance

(www.linkedin.com/groups/12304531/)

Our group's mission is to create a global community among professionals who use, develop, market, or support Product Lifecycle Management (PLM) enabling technologies and software solutions…that have a role in creating a more sustainable, low-carbon circular economy.

Future Chemistry Network

(www.linkedin.com/groups/9088322/)

Cefic (an initiative of the European Chemical Industry Council) has created this group to foster a multi-stakeholder discussion on innovation and policy developments in sustainable chemistry.

Clean Technology: Discussion Forum

(www.linkedin.com/groups/14033041/)

Let us share positivity on how best to serve our planet and environment!

Climate Change, Sustainability & ESG Network

(www.linkedin.com/groups/114382/)

This group is for professionals and enthusiasts who are interested in networking with fellow experts to collaborate on Climate Change, Sustainability & ESG initiatives.

SERF (Sustainable Engineering Research Forum)

(www.linkedin.com/groups/2294225/)

The Sustainable Engineering Research Forum (SERF) is an online community aimed at forming and developing connections between engineering professionals interested in environmentally related research areas.

Carbon Footprint Forum

(www.linkedin.com/groups/83858/)

This is a forum group for discussing Carbon Footprint Best Practices and Issues among organizations, companies, consultants, and carbon market experts.

Clean Planet for All

(www.linkedin.com/groups/81197/)

The aim of the group is to develop cheap technologies for a clean planet for everyone, and it calls especially for ideas and best practices.

International Society for Industrial Ecology (ISIE)

(www.linkedin.com/groups/734507/)

ISIE promotes industrial ecology as a way of finding innovative solutions to complicated environmental problems, and facilitates communication among scientists, engineers, policymakers, managers,

and advocates who are interested in how environmental concerns and economic activities can be better integrated.

Recyclers

https://www.linkedin.com/pulse/sustainable-engineering-linkedin-groups-roger-l-franz-cnxac
https://www.linkedin.com/pulse/sustainability-circularity-linkedin-groups-roger-l-franz-zuf3c

Here we list groups focusing on material recycling. This is where circularity is accomplished by returning end-of-life products back to useful materials to be reused again.

Given the materiality of these processes, listings include companies and organizations performing physical services beyond LinkedIn discussion groups. Here is where talk about circularity is brought down to Earth.

e-Stewards Certified Recyclers

(www.linkedin.com/groups/2918667/)

This group is for e-Stewards recyclers to share information about our industry and help each other by providing a place to post information that may be relevant to our collective unique position in the marketplace.

e-waste management

(www.linkedin.com/groups/1781114/)

This group is for people/corporates to exchange ideas about e-waste management/disposal. This group will provide a platform for networking among people for e-waste disposal and collection activities.

The Recycled Materials Association (ReMA)

(https://recycledmaterials.org/)

ReMA represents more than 1,700 companies in the United States and 40 countries around the globe. Based in Washington, DC, ReMA

provides advocacy, education, safety, and compliance training, and promotes public awareness of the vital role recycled materials play in the US economy, global trade, the environment, and sustainable development.

https://www.linkedin.com/groups/3422165/

Bureau of International Recycling (BIR)

(www.bir.org/)

Founded in 1948, BIR was the first federation to support the interests of the recycling industry on an international scale. Today, BIR represents more than 30,000 companies around the globe, with a direct membership of over 950 companies and 38 national associations from 70 countries. Together, these members form the largest international recycling federation.

The Recycle Global Exchange (RGX)

(https://recyclegx.com/)

The Recycle Global Exchange (RGX) marketplace connects businesses directly with local, certified vendors to dispose of e-waste responsibly and efficiently. Our process decreases carbon footprints while increasing ROI with competitive bidding and resource management.

RIOS: The Recycling Industry Operating Standard

(www.rioscertification.org/)

The Recycling Industry Operating Standard (RIOS) is the recycling industry's management system standard for quality, environment, health, and safety (QEH&S). Recycling facilities that process materials including brass, copper, electronics, ferrous metals, glass, lead, magnesium, paper, rubber, precious metals, textiles, tin, zinc, and more.

Plastic Scrap and Recycling Plastic Pellets and Discussions and New Startups in Plastic Industry

(www.linkedin.com/groups/8371304/)

Creation of this Group to promote the plastic industry, especially those who are involved in plastic scrap and recycling business.

Material Recycling Association of India

(www.mrai.org.in/)

MRAI is an apex National Association, representing the interests of the Indian Recycling Industry.

Phoenix Recycling Group

(www.phoenixrecycling.co.nz/)

Welcome to Phoenix Recycling Group. We are proudly 100% NZ-owned. We are a nationwide recycling business, facilitating solutions that deliver the circular economy of multiple materials and products through its supply chain; locally and globally; end-to-end.

Key Takeaways

This listing of groups and associations supporting sustainability in general and electronics and related technical aspects in particular is intended to be a valuable addition to the rest of this book, which is primarily based on literature and other more formal publications. Take advantage of these opportunities and contribute to them if you can.

Next, we move on to our last chapter, which closes this book with a retrospective perspective.

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9. Retrospective Perspective

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The previous chapters

- covered the awareness of WITS (what's in this stuff) and what substances in electronics could be unhealthy
- detailed how this data is being shared across the electronics supply chain
- explained how standards and tools are available to help if we only use them
- speculated on making more use of carbon rather than practically every element in the periodic table
- shared some successes in circularity and energy efficiency, with some fast-growing problems as well
- invited interested parties to work together with links to social media groups
- shared a dictionary of upcoming technologies as a kind of alphabet soup without a specific recipe

To close out this book, this chapter covers a few even larger perspectives to consider.

These final pages will go even further outside the mainstream of current technology. Think big. Think globally. Think long term. Think cosmic.

Figure 9-1 reminds us of who we are on this small planet, third from the Sun. This simple picture of our solar system does not show the

history of how all the minerals came to be on Earth, nor do we want to explain all of that here. But ultimately, the quest for sustainability does beg to ask some very big questions about using the materials available to us in a more sustainable way.



Figure 9-1 Group IV-A of the periodic table

What you will take away from this chapter

- How an industry-wide change to lead-free solder fulfilled a larger unseen destiny
- How progress from heavy (and toxic) metals up the periodic table to our common life-based element carbon makes long-term sense

- How reversing the technology-driven paradigm of “faster is better” has more sustainable alternatives
- How the understanding pre-technology cultures holds valuable truths for us today
- How the use of carbon nanotechnology may resolve the basic conflict of conductors (metals) vs. insulators (non-metals)

Planets in Motion Success Story: Solder

The evolution of tin-lead solder to lead-free, as discussed in this book, has an underlying message hidden in the ancient arts, astrology, and alchemy. The message is based on the belief that the known metals and visible planets at the time were connected to each other. The solder story has just four players.

- **Lead** was traditionally associated with the planet **Saturn**
- **Tin** was aligned with **Jupiter**
- **Copper** was represented by **Venus**
- **Silver** was seen in the **Moon**

By replacing traditional tin-lead alloy with tin-silver-copper, we see the lead going away from Saturn, the most distant planet recognized by the ancients, with tin remaining in the planet next closest to the Sun—the largest and most dominant planet, Jupiter. The second member of the alloy—copper—continues moving into the inner planets of the solar system as associated with Venus. Finally, the third member is silver, associated with the Moon. These modern solder alloys are now providing electrical connections all around us.

From ancient planetary correspondences with alchemical metals, this leaves only iron, associated with Mars, and mercury, corresponding to the planet Mercury. The remaining metal associated with the Philosopher’s Stone itself is gold, associated with the Sun.

And while in reality the new solder was identified and proven by scientific metallurgists and manufacturing engineers, sustainable dreaming of the ancient arts brings us to the same place.

Straight Up to Circularity

Similarly, we see the overall progression of elements in Group IV of the modern periodic table. Aligning with the vector of continual technical progress that turns into the circular promise of sustainability, the movement that is in process is clear and revealing.

Figure 9-1 shows column IV of the periodic table of the elements. First, let us look at it from the top down, then in the more historical order from bottom to top.

At the top of the column is carbon (C). Nature is built around carbon, along with a few other elements. Can electronics do something similar? This is an important challenge in this book.

Below carbon, silicon (Si) is the darling of the semiconductor age and the substrate upon which Moore's law was built.

Next down is germanium (Ge), a semiconductor used in early devices like diodes and transistors. While still used, the semiconductor spotlight has moved above it to silicon (Si).

Germanium and silicon were unknown in the ancient art of alchemy and similarly not related to astrology with any planetary association.

Below germanium is tin (Sn), which was often alloyed with lead in the example of traditional electronics solder. Tin itself remains a lead-free conductor and component termination material.

Starting at the bottom is lead (Pb), which, as noted, is an ancient metal in need of replacement due to its toxicity, but is so often found in today's electronics, including metal alloys and components made with leaded glass or ceramics.

Finally, if there is a planet associated with carbon on top, clearly it is Earth.

This progression of the elements in history from lead on up to carbon summarizes our theme. Sustainable electronics, or other goods for that matter, cannot achieve sustainability without new materials designed from the outset to be sustainable. In the beginning of this book, we highlighted the conflict between conductors (traditionally organic) and insulators (traditionally metals) that make existing components highly difficult to separate, recycle, and reuse. Carbon may

offer such a new path since, in the right configuration, it can be made into both.

The future is organic electronics.

Slow Down Time

Since its early days, electronics technology has pursued faster and faster performance and higher and higher frequencies. We close this book with the thought that truly big picture possibilities need to be considered, in fact, as big as the creation of Earth itself from the stars.

First, however, it may be worth reviewing the hertz (Hz), which is the fundamental unit of measurement in terms of cycles per second. To begin with a familiar frequency, the human heartbeat tends to be roughly one Hz; that is, one per second. What we hear with the human ear is up in the audio range between 20 Hz and 20,000 Hz.

Moving to higher frequencies, we soon encounter radio waves. Their frequencies continue up beyond infrared, visible, and ultraviolet light, to an almost unimaginable number of Hz in gamma rays. You can see the frequency spectrum shown in Figure 9-2 at https://ised-isde.canada.ca/site/spectrum-management-telecommunications/en/licences-and-certificates/introduction-radio-frequency-spectrum.

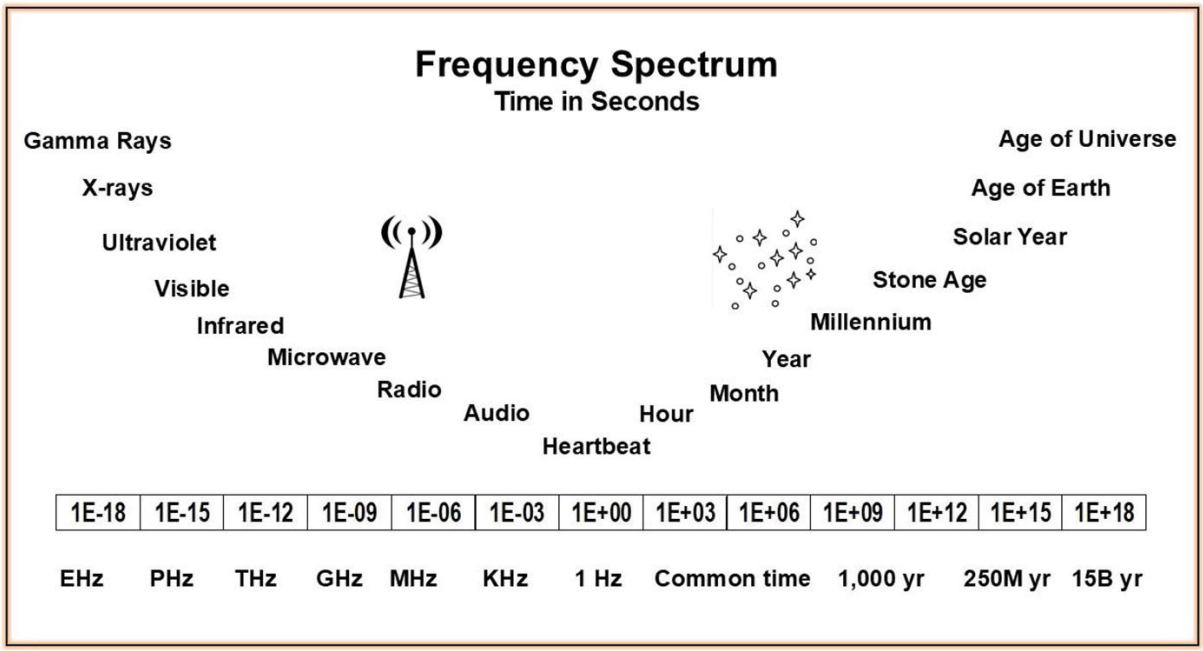


Figure 9-2 2 Full frequency spectrum

Much of this book on the theme of sustainability suggests we go in just the opposite direction: to slow down, stop consuming, and extend the lifetime of products. This thinking may be extended to connect with the slow cycles of nature, which are not often discussed in the same sentence as frequencies because they are less than one cycle per second.

To visualize this aspect of longer time, Figure 9-2 expands the typical electromagnetic spectrum in a new way. Instead of using cycles per second, the axis shows the inverse metric of seconds per cycle. So, for example, fast radio and electronic waves on the left repeat in a small fraction of a second. On the far right are longer cycles extending from the human heartbeat of about one second per beat to the familiar measures of days, months, and years. Beyond that lie very long periods thousands, millions, or higher orders of magnitude of seconds on a cosmic scale. While the intent is not to say that these long periods can be treated as conventional electromagnetic radiation, it is these long periods of time that cannot be replaced but must be recognized to appreciate how long it took to form the chemical elements we take for

granted today. In this context, sustainability includes the dimension of longevity and the time dimension of nature herself.

An Earth day of 24 hours is 86,400 seconds; in terms of cycles per second, that is 1/86,400 or just 0.00001 Hz.

With so many zeros, it may make sense to follow the typical representation of higher frequencies, using powers of ten and their recognized English prefixes. (We are not trying to prove that these very slow events are the exact equivalent to waves of electromagnetism, but to simply show in numbers how slowing down helps gain a perspective on sustainability.) Consider these familiar events in terms of the inverse cycles per second (Hz); that is, seconds per cycle, which beyond one day becomes very large numbers of seconds.

- Day (24 hours) 86,400 seconds
- Lunar month (28 days) or 2,419,200 seconds
- Earth year (365 days) or 31,536,000 seconds
- Millennium (1,000 years) or 31,536,000,000 seconds

Going even beyond those slow events, we may even consider the times on a grand geological scale (see www.sciencenewstoday.org/the-history-of-earth-a-journey-through-deep-time):

- Earth formation: 4.5 billion years ago
- First life on Earth: 3.8 billion years ago
- Supercontinents: 2.7 billion years ago
- Earth's atmosphere is enriched with oxygen: 2.4 billion years ago
- Cambrian period and multicellular life: 540 million years ago
- Life from oceans to land: 470 million years ago
- Dinosaurs: 252 million years ago
- The great cataclysm: 66 million years ago
- Erect-walking apes: 6 million years ago
- Homo sapiens: 300,000 years ago

The formation of minerals and metals, many of which have been discussed in prior chapters, was a very long series of complicated

events. In the context of circularity, the ideal goals would be to return Earth's minerals and other resources to a state that existed before mankind disturbed the natural state. Practically, of course, we cannot possibly hope to repeat the formation of Earth and its reserves of minerals. But awareness of all that has gone before us and the times involved may spur new big ideas to connect with our history of this planet. Think about long strokes of time to achieve long-term results.

Sustainability is not just about material technology; it is also about time. This is the essence of the definition introduced in the opening pages of this book: "…to make development sustainable—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. In essence, sustainability is about time.

Minerals Have a Life

As many indigenous cultures have taught for centuries, the non-biological diversity around us is not simply dead matter. Everything is infused with vibrations, from the wavelengths of infrared heat and microwave frequencies of molecular motion, to the electronic clouds around all matter which have their own unique spectra, to the nucleus of each atom which lives in the X-ray region as detected by that type of spectroscopy.

Minerals have not just been static on this planet after being deposited here by the stars and meteorite impacts. Rather, "the mineral kingdom is an example of a nonliving system that has systematically increased in diversity and complexity through Earth's 4.56-billion-year history." (See https://academic.oup.com/pnasnexus/article/3/7/pgae248/7698354.)

Another way of saying this in terms of a question is, "Life evolves. How about everything else?" The question has an answer: Minerals evolve too.

The big picture connections between minerals, which are the raw materials for all electronic hardware, and time itself are not random. The concept of circularity, when truly embraced, does really get this large.

One final note: Earth is not just a thing. She is alive:

Her blood flows in the rivers
Mountains joining sky to land
Storms express her many emotions
Rainbows are her loving hand

From “Alive is She” in the poetry collection *Indivisible* by Roger Hammer (pen name of the author).

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Table 6-1 Summary of Standards for Longer Life Products

Summary of Standards and Related Documents

Document	Design and Materials Selection	Reliability and Maintainability	Recovery and Recycling
IEC 62430 – Environmentally conscious design for electrical and electronic products	x		
IEC Technical Specification 63428 – Guidance on material circulation considerations in environmentally conscious design	x		
EN45560 – Method to achieve circular designs of products	x		
IEC Technical Specification 63428 – Guidance on material circulation considerations in environmentally conscious design	x		
IEC 61709:2017 Electric components - Reliability – Reference conditions for failure rates and stress models for conversion		x	
Guidelines to Understanding Reliability Prediction – European Power Supply Manufacturers Association		x	
MIL-HDBK-217F – Reliability Prediction of Electronic Equipment		x	
MIL-STD-202G Test Method Standard Electronic and Electrical Component Parts		x	
MIL-STD-1629A – Procedures for Performing a Failure Mode Effects and Criticality Analysis P		x	
Mil-HBK-472 - Maintainability Prediction		x	
EN 50625-Part 5 – Specification for the final treatment of WEEE fractions – Copper and precious metals			x
ReMA (Recycled Materials Association) Specifications Circular			x

Table 2-1 The Number of SVHCs Containing Halogens and Phthalates Is SignificantSource: Author data: European Chemicals Agency, 2026

Total SVHC	253
Contain halogen (F, Cl, Br)	140
Phthalates	21