

THIRD EDITION



Materials and the Environment

Eco-Informed Material Choice

Third Edition

Michael F. Ashby



Butterworth-Heinemann
An imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2021 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the Publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website:
www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher, nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

ISBN: 978-0-12-821521-0

For information on all Butterworth-Heinemann publications visit our website at
<https://www.elsevier.com/books-and-journals>



Publisher: Katey Birtcher
Acquisition Editor: Stephen Merken
Editorial Project Manager: Alice Grant
Production Project Manager: Rukmani Krishnan
Cover Designer: Renee Duenow

Typeset by TNQ Technologies

Preface

The environment is our life-support system. Modern society may seem sophisticated, but there are some very simple things we all need: clean air, productive land and oceans, pure fresh water, a healthy biosphere, material and energy resources, and a stable climate. The considerable demands that society now puts on these have become increasing concerns. As we enter the fourth industrial revolution (“Industry 4.0”), our dependence on material resources, already large, notches up yet further—“Materials 4.0” is an attempt to keep pace with it.

The environment is a system. Human society, too, is a system. The systems coexist and interact, weakly in some ways, strongly in others. When two already complex systems interact, the consequences can be hard to predict. One consequence has been the damaging impacts of industrial society on the environment and the ecosystem in which we live and on which we depend. Some, like the devastation caused by mining, have been evident for more than a century, prompting remedial action that, in many cases, has been successful. Others, emerging only now, were unanticipated, among them the influence on global climate. Materials are implicated in many of these problems. If we are going to do anything about them, we must first understand their origins. And that needs *facts*.

The book. This text is a response. It aims to cut through some of the oversimplification and misinformation that permeate much discussion about the environment. It explains the ways in which we depend on and use materials and the consequences these have. It introduces methods for thinking about and designing with materials when the objective is to minimize environmental impact, one that is often in conflict with others, particularly that of minimizing *cost*. It does not aim to provide ultimate solutions but rather to provide perspective, background, methods, and data—a toolbox, so to speak—to introduce one of the central issues of environmental concern: the impact of materials and the ways we use them on the environment.

The text is written primarily for students of engineering and materials science in any one of the 4 years of an undergraduate program. It is in two parts. The first—Chapters 1 to 14—develops the background and tools required for the materials scientist or engineer to analyze and respond to environmental imperatives. The second—Appendices A and B—is an assembly of curated data needed for analysis.

The two together allow case studies and provide resources on which students can draw to tackle the exercises at the end of each chapter (for which a solution manual is available).

To understand where we now are, it helps to look back over how we got here. Chapter 1 gives a history of our increasing dependence on materials and energy. Most materials are drawn from nonrenewable resources inherited from the formation of the planet or from geological and biological eras in its history. Like any inheritance, we have a responsibility to pass them on to further generations in a state that enables them to meet their aspirations as we now do ours. The volume of these resources is enormous, but so too is the rate at which we are using them. A proper perspective here needs both explanation and modeling. That is what Chapter 2 does.

Products, like plants and animals, have a life cycle, one with a number of phases, starting with the extraction and synthesis of raw materials (“birth”) and continuing with their manufacture into products, which are then transported, used (“maturity”), and, at the end of life, sent to landfill or to a recycling facility (“death”). Almost always, one phase of life consumes more resources and generates more emissions than all the others put together. The first job is to identify which phase it is. Life-cycle assessment (LCA) seeks to do this, but there are problems: as currently practiced, LCA is expensive, slow, and delivers outputs that are unhelpful for engineering design. One way to overcome them is to focus on the main culprits: one resource—*energy*—and one emission—*carbon dioxide*, CO_2 . Materials have an *embodied energy* (the energy it takes to create them) and a *carbon footprint* (the CO_2 that creating them releases). So, too, do the other phases of life, and materials play a central role in these also. Heating and cooling and transport, for instance, are among the most energy-gobbling and carbon-belching activities of an industrial society. The right choice of materials can minimize their appetite for both. This line of thinking is developed in Chapters 3 and 4, from which a strategy emerges that forms the structure of the rest of the book.

Governments respond to environmental concerns in a number of ways applied through a combination of sticks and carrots, or, as they would put it, *command and control* methods and methods exploiting *market instruments*. The result is a steadily growing volume of legislation and regulation that, like it or not, requires compliance. They are reviewed in Chapter 5.

As engineers and scientists, our first responsibility is to use our particular skills to guide design decisions that minimize or eliminate adverse eco-impact. Properly informed materials selection is a central aspect of this, and that needs data for the material attributes that bear most directly on environmental questions. Some, like *embodied energy* and *carbon footprint*, *recycle fraction* and *toxicity*, have obvious eco-connections. But more often it is not these but mechanical, thermal, and electrical properties that have the greatest role in design to minimize eco-impact. The data sheets of Appendices A and B provide all of these. Data can be deadly dull. It can be brought to life (a little) by good visual presentations. Chapter 6 introduces

the material attributes that are central to what follows and displays them in ways that give a visual overview.

Now to *design*. Designers have much on their minds. They can't wait for (or afford) a full LCA every time a material choice arises. That is where an *eco-audit* can help. It is a fast assessment of product life comparing the impact of each phase, suggesting where redesign might offer the greatest gain, and allowing rapid "what if" trials to compare alternatives. Chapter 7 introduces eco-audit methods. They are illustrated by case studies in Chapter 8.

The eco-audit points to the phase of life of most concern. What can be done about it? In particular, what material-related decisions can be made to minimize its eco-impact? Material selection methods are the subject of Chapter 9. They form a central part of the strategy that emerged from Chapter 3. It is important to see them in action. Chapter 10 presents case studies of progressive depth to illustrate ways of using them. The exercises suggest more.

Could renewable materials, derived wholly or in part from nature, play a larger role in the engineering economy of the 21st century? Many people think they should. The question is explored in Chapter 11, which reviews bio-based polymers and composites and surveys the field of fibers, comparing synthetic fibers with those derived from plant and animal sources that, until 1960, dominated the market.

Access to material resources is an issue that increasingly preoccupies governments and industries. At a national level, a "critical" material is one that plays a key role in the economy and security of a nation but has a supply chain that may be constrained or unstable. At the level of an industrial enterprise, the perception of criticality is more product-centric, focusing on the supply risk for the materials in the company's product range and substitutes for them if they become unavailable. Chapter 12 examines the origins of criticality and supply-chain risk, particularly those relating to environmental constraints.

Natural and industrial systems transform resources, meaning materials and energy, to provide functionality. Natural systems are circular—the materials on which organisms depend return to the pool of natural resources when the organism dies. Industrial systems, at present, are not like that; the materials on which they depend become "waste" at end of life, accumulating in landfills and polluting soil and water. Chapter 13 surveys the ongoing transition to a more circular materials economy, highlighting successes and analyzing limitations.

Chapter 14, the final chapter, approaches the difficult topic of sustainability, exploring metrics for the three key components: natural capital, manufactured and financial capital, and human and social capital. Comparison at the international level shows large differences in the demands populations make on the environment and the measures they take to protect it. The chapter brings together (environmental) LCA, life-cycle costing, and the emerging methods of social LCA to develop a more complete picture. It ends with a survey of corporate sustainability reporting and the ways in which population, affluence, and technology interact to increase or reduce eco-burden.

Access to reliable data, as already mentioned, is essential if meaningful judgments are to be made. Appendix A lists engineering properties for selected materials. Appendix B does the same for eco-properties, both for materials and for transport.

What's new in the 3rd edition? The basic structure of the book remains the same as that of earlier editions, but within this structure there are many changes. These are partly in response to feedback from users of the 1st and 2nd editions and partly necessitated by the rapid evolution of the study of materials and the environment. Here is a summary:

- All chapters and the data, diagrams, examples, and case studies they contain have been edited, expanded, and brought up to date.
- All engineering and environmental data have been reviewed and updated. The new Appendix A lists engineering properties for 62 selected materials. Appendix B lists environmental and supply-chain data for the same 62 materials, with additional data for precious and refractory metals and rare-earth elements; electronic components; building materials; shaping, joining, and finishing processes; and transport.
- Newsclips are incorporated into all the chapters. These are cuttings from the world press that help place materials issues into a broader context.
- There are new or extensively revised chapters on renewable materials and fibers, material criticality, circular materials economics, and sustainable development.
- There are over 200 exercises with worked solutions, grouped by chapter, all updated to be consistent with the data in the two appendices. A solution manual is available from the publisher.
- Further reading at the end of each chapter has been brought up to date with new citations.

Feedback from readers of past editions has been a great help in guiding this new one. Criticisms and suggestions from current readers will be very welcome.

The CES software.¹ The audit and selection tools developed in the text are implemented in the CES EduPack software, a powerful materials-information system that is widely used for both teaching and design. The book is self-contained; access to the software is not a prerequisite. The software is a useful adjunct to the text, enhancing the learning experience and providing access to data for a much wider range of materials. It allows realistic selection studies that properly combine multiple constraints and the exploration of trade-offs between the conflicting objectives of environment, cost, and human welfare.

¹Anslys Granta, 300 Rustat House, 62 Clifton Road, Cambridge CB1 7EG, UK, <https://www.ansys.com/products/materials/granta-edupack/>.

Acknowledgments

No book of this sort is possible without advice, constructive criticism, and ideas from others. Numerous colleagues have been generous with their time and thoughts. I would particularly like to recognize the suggestions and stimulus, directly or indirectly, made by Dr. Julian Allwood, Professor David Cebon, Dr. Jon Cullen, and Professor David MacKay, all of Cambridge University; Professor Yves Bréchet of the University of Grenoble; Professor John Abelson of the University of Michigan; Professor Mark De Guire of Case Western Reserve University; Robert O. Vos of the University of Southern California; Dr. Deborah Andrews of London South Bank University; and Dr. Tatiana Vakhitova and Dr. Claes Fredriksson of Granta Design, Cambridge. Equally valuable has been the contribution of the team at Granta Design, Cambridge, responsible for the development of the CES software that has been used to make a number of the charts that appear in this book.

Mike Ashby
Cambridge, UK
March 2020

Introduction: material dependence



CONTENTS

- 1.1 Introduction and synopsis
- 1.2 Materials: a brief history
- 1.3 Industrial revolutions: the growing reliance on nonrenewable materials
- 1.4 Materials and the environment
- 1.5 Summary and conclusions
- 1.6 Further reading
- 1.7 Exercises

Differing ecological footprints. Top: Indian village reconstruction. (Image courtesy of Kevin Hampton <http://www.wm.edu/niahd/journals>). Bottom: Tokyo at night. (Image courtesy of <http://www.photoeverywhere.co.uk> index)

1.1 Introduction and synopsis

This book is about *materials and the environment*: the eco-aspects of their production, their use, and their disposal and resurrection at end of life. It is also about ways to choose and design with them in ways that minimize the impact they have on the environment. To do that you need data and an understanding of their limitations; that's here too.

Environmental harm caused by industrialization is not new. The manufacturing midlands of 18th-century Britain acquired the name of the “Black Country” with good reason; and to evoke the atmosphere of 19th-century London, Sherlock Holmes movies show scenes of fog—known as a “pea-souper”—swirling round the gas lamps of Baker Street. These were localized problems that have, today, largely been corrected. The change now is that some aspects of industrialization begin to influence the environment on a global scale. Materials are implicated in this. As responsible materials engineers and scientists, we should try to understand the nature of the problem—it is not simple—and to explore what, constructively, can be done about it.

This chapter introduces the key role materials have played in advancing technology and the dependence—addiction might be a better word—that this has bred. Addictions demand to be fed, and this demand, coupled with the continued growth of population, consumes resources at an ever-increasing rate. This has not, in the past, limited growth; the earth's resources are, after all, very great. But there is increasing awareness that limits *do* exist, that we are approaching some of them, and that adapting to them will not be easy.

1.2 Materials: a brief history

Materials have enabled the advance of humankind from its earliest beginnings; indeed, advances in humanity are named after the dominant material of the day: the *Stone Age*, the *Age of Copper*, the *Bronze Age*, the *Iron Age*, the *Age of Silicon* (Fig. 1.1). The tools and weapons of prehistory, 300,000 or more years ago, were bone and stone. Stones could be shaped for tools, particularly flint and quartz, which could be flaked to produce a cutting edge that was harder, sharper, and more durable than any other naturally occurring material. Simple but remarkably durable structures could be built from the materials of nature: stone and mud bricks for walls, wood for beams, and bark, rush, and animal skins for roofing.

Gold, silver, and copper, the only metals that occur in native form, must have been known from the earliest time, but the realization that they were ductile, could be beaten into complex shapes, and, once beaten, became hard seems to have come around 5500 BCE. By 4000 BCE the ability to melt and cast these metals had developed, allowing more intricate shapes. Native copper, however, is not abundant. Copper occurs in far greater quantities as the minerals azurite and malachite. By 3500 BCE, kiln furnaces, developed for pottery, could reach the temperature and create the atmosphere needed to reduce these minerals, allowing the

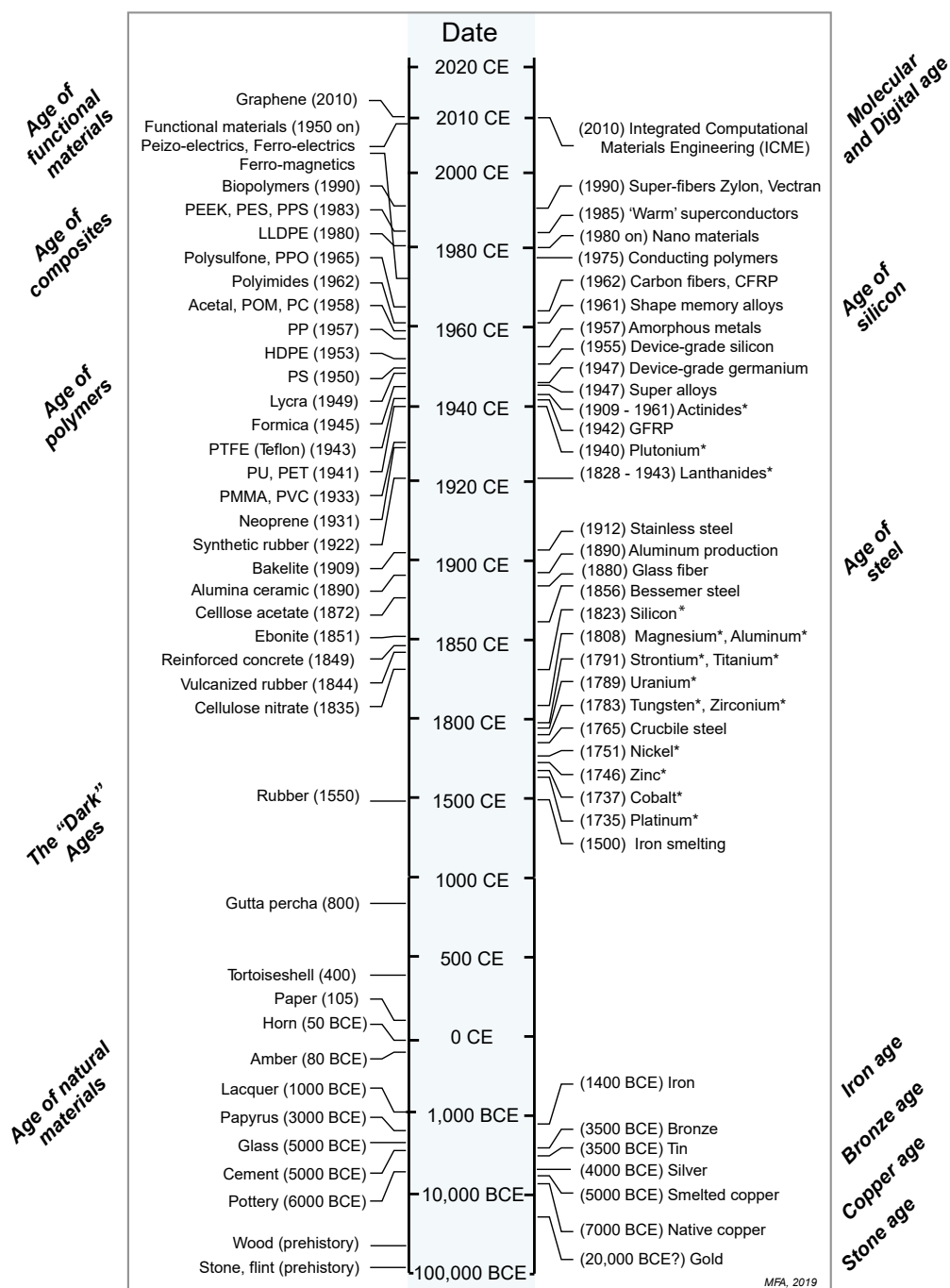


FIGURE 1.1 The materials timeline. The scale is nonlinear, with big steps at the bottom, small ones at the top. An asterisk (*) indicates the date at which an element was first identified. Unmarked labels give the date at which the material became of practical importance.

development of the tools, weapons, and ornaments that we associate with the Copper Age.

But even in the worked state, copper is not all that hard. Poor hardness means poor wear resistance; copper weapons and tools were easily blunted. Sometime around 3000 BCE the probably accidental inclusion of a tin-based mineral, cassiterite, in the copper ores provided the next step in technology: the production of the copper–tin alloy *bronze*. Tin gives bronze a hardness that pure copper cannot match, allowing the production of superior tools and weapons. This discovery of alloying—the hardening of one metal by adding another—stimulated such significant technological advances that it, too, became the name of an era: the Bronze Age.

“Obsolescence” sounds like 20th-century vocabulary, but the phenomenon is as old as technology itself. The discovery, around 1450 BCE, of ways to reduce ferrous oxides to make iron, a metal with greater stiffness, strength, and hardness than any other then available, rendered bronze obsolete.

Metallic iron was not entirely new: tiny quantities existed as the cores of meteorites that had impacted the earth. The oxides of iron, by contrast, are widely available, particularly *hematite*, Fe_2O_3 . Hematite is easily reduced by carbon, although it takes temperatures close to 1100°C to do it. This temperature is insufficient to melt iron, so the material produced was a spongy mass of solid iron intermixed with slag that was reheated and hammered to expel the slag, and then forged to the desired shape. Iron revolutionized warfare and agriculture; indeed, it was so desirable that at one time it was worth more than gold. The casting of iron, however, presented a more difficult challenge, requiring temperatures around 1600°C . There is evidence that Chinese craftsmen were able to do this as early as 500 BCE, but two millennia passed before, in 1500 CE, the blast furnace was developed, enabling the widespread use of cast iron. Cast iron allowed structures of a new type: the great bridges, railway terminals, and civil building of the early 19th century are testimony to it. But it was steel, made possible in industrial quantities by the Bessemer¹ process of 1856, that gave iron its dominant role in structural design that it still holds today. For the next 150 years, metals dominated manufacture. The demands of the expanding aircraft industry in the 1950s shifted emphasis to the light alloys (those based on aluminum, magnesium, and titanium) and to materials that could withstand the extreme temperatures of the gas turbine combustion chamber (superalloys—heavily alloyed iron- and nickel-based materials). The range of application of metals expanded into other fields, particularly those of chemical, petroleum, and nuclear engineering.

The history of polymers is rather different. Wood, of course, is a polymeric composite, one used for construction from the earliest times. The beauty of

¹Sir Henry Bessemer (1813–1898) was the English inventor of the process that made most of the world’s steel between 1856 and 1950. His many other inventions included a way of making bronze powder and gold chains. Unlike most inventors, he brought many of his projects to fruition, kept the details secret, and grew rich in the process.

amber—petrified resin—and of horn and tortoiseshell—the polymer keratin—attracted designers as early as 100 BCE, and continued to do so into the 19th century (there is still, in London, a horners' guild, the trade association of those who worked horn and shell). Rubber, brought to Europe in a remarkable heist² in 1876, grew in importance in the late 19th century, partly because of the wide spectrum of properties made possible by vulcanization—cross-linking by sulfur—to create materials as elastic as latex and others as rigid as ebonite.

The real polymer revolution, however, has its beginnings in the early 20th century with the development of Bakelite,³ a phenolic, in 1909 and of synthetic butyl rubber in 1922. This was followed in midcentury by a period of rapid development of polymer science, visible as the dense group at the upper left of Fig. 1.1. The polymers we use today in the greatest quantities were developed in a 20-year span from 1940 to 1960, among them polypropylene, polyethylene, poly(vinyl chloride), and polyurethane, the combined annual tonnage of which now approaches that of steel. Designers seized on these new materials—they were cheap, brightly colored, and easily molded into complex shapes—to produce a spectrum of cheerfully ephemeral products. Design with polymers has since matured: they are now as important as metals in household products and automobile engineering, and have become an environmental problem on a global scale.

The use of polymers in high-performance products required a further step. “Pure” polymers do not have the stiffness and strength these applications demand; to provide it they must be reinforced with ceramic or glass fillers and fibers, making *composites*. Composite technology is not new. Straw-reinforced mud brick (adobe) is one of the earliest of the materials of architecture, one still used today in parts of Africa and Asia. Steel-reinforced concrete—the material of shopping centers, road bridges, and apartment blocks—appeared just before 1850. Reinforcing concrete with steel gives it tensile strength where previously it had none, revolutionizing architectural design; it is now used in greater volume than any other human-made material. Reinforcing metals, already strong, took much longer, and even today, metal-matrix composites are few.

The second half of the 20th century might have been named the Polymer Age had it not coincided with yet another technical revolution, that based on silicon. Silicon was first identified as an element in 1823, but found few uses until the realization, in 1947, that, when doped with tiny levels of impurity, it could act as a rectifier. The discovery created the fields of electronics and modern computer

²The production of rubber was a heavily protected South American monopoly until 1876, when Henry Wickham, British explorer and bio-pirate, stole 70,000 rubber tree seeds and delivered them to Kew Gardens, from where seedlings were sent to the British colonies, notably Malaysia. Malaysia is now the world's largest producer of latex rubber.

³Leo Hendrik Baekeland (1863–1944), Belgian chemist and inventor, developed the first commercially successful photographic paper (Velox), which he sold to George Eastman for the colossal sum (in 1899) of \$1,000,000. From our point of view his most significant invention was that of the first thermosetting plastic, which he modestly named Bakelite.

science, revolutionizing information storage, access, and transmission; imaging; sensing and actuation; automation; and real-time process control.

Material behavior depends on scale. The dependence is most evident when the scale is that of nanometers (10^{-9} m). Although the term *nanoscience* is new, technologies that use it are not. The ruby red color of medieval stained glasses and the diachronic behavior of the decorative glaze known as “luster” derive from gold nanoparticles trapped in the glass matrix. The light alloys of aerospace derive their strength from nanodispersions of intermetallic compounds. Automobile tires have, for years, been reinforced with nanoscale carbon. Modern nanotechnology gained prominence with the discovery that carbon could form stronger structures: spherical C_{60} molecules and rodlike tubes and atomic-scale layers (graphene). Now, with the advance of analytical tools capable of resolving and manipulating matter at the atomic level, the potential exists to build materials the way that nature does it, atom by atom and molecule by molecule.

Developments in thermochemistry, electrochemistry, and nanochemistry have greatly expanded the materials menu. The next major expansion, now under way, is that brought about by what might be called digital chemistry. Integrated Computational Materials Engineering (ICME, 2008, ongoing) links computer models that span length scales (“atoms-to-airplanes”) to design new materials for specific applications. The Material Genome Initiative (MGI, 2011, ongoing) integrates theory, computation, synthesis, and characterization to develop new materials more quickly. These are in part driven by advances in computational modeling and simulation and in part by advances in data-gathering techniques such as combinatorial experimentation (characterizing a range of process variables, like compositions, in a single graded test sample) and by the flood of data from materials and components in service made possible by the Internet of things (IoT).

If we now step back and view the timeline of Fig. 1.1 as a whole, clusters of activity are apparent: there is one in Roman times, one around the end of the 18th century, one in the mid-20th. What was it that triggered the clusters? Scientific advance, certainly. The late 18th and early 19th centuries was the time of rapid development of inorganic chemistry, particularly electrochemistry, and it was this that allowed new elements to be isolated and identified. The mid-20th century saw the birth of polymer chemistry, spawning the polymers we use today and providing key concepts in unraveling the behavior of the materials of nature.

But there may be more to it than that. Conflict stimulates science. The first of these two periods coincides with that of the Napoleonic Wars (1796–1815), one in which technology, particularly in France, developed rapidly. And the second was that of the Second World War (1939–1945), in which technology played a greater part than in any previous conflict. Defense budgets have, historically, been prime drivers for the development of new materials.

This is still the case today. But scientific progress and advances in materials are possible without conflict, and the competitive drive of free markets can be an equally strong driver of technology. It is interesting to reflect that more three-quarters of all the materials scientists and engineers who have *ever* lived are alive

today, and all of them are pursuing better materials and better ways to use them. Of one thing we can be certain: there are many more advances to come.

1.3 Industrial revolutions: the growing reliance on nonrenewable materials

Some 2.5 million years ago, somewhere in East Africa, humans discovered how to make and use tools. Tools allowed new subsistence patterns, the occupation of new environmental zones, and ultimately the spread of *Homo sapiens* across the globe. It was the original industrial revolution, deploying wood, stone, animal skin, and bone to create shelter, weapons, and clothing (Fig. 1.2).

The title of First Industrial Revolution attaches to the one that followed. It started in Britain around 1760 and spread, over the next 60 years, across Europe and around the world. Its enabling material—cast iron—allowed water and steam power to replace hand production methods, particularly in the textile and mining industries. Mechanization allowed enormous gains in productivity, though much of what was produced remained in the hands of the wealthy.

The Second Industrial Revolution coincided with the era of the great inventors and builders in the second half of the 19th century: Edison, Bell, Marconi, Brunel, Henry Ford, Eiffel, and many more. Mass production made goods available to many people, not just to the wealthy few. Steel, copper, rubber, and glass replaced the older materials of construction and transport; manufacturing thrived; urbanization created new communities; international trade spread goods and ideas across the Western world.

Productivity was stimulated further by a Third Industrial Revolution that gathered pace in the 1970s as silicon-based technologies combined with advanced software, robotics, and new processes to create digital manufacturing systems. Manufacture became more flexible; products could be customized to serve niche markets, further stimulated by the wide availability of plastics and composites, the new commodity materials.

We are now (2020) immersed in the Fourth Industrial Revolution (“Industry 4.0”). This is the age of connectivity. Social media and mobile communication connect people, the IoT connects products, and emerging (but still imperfect) artificial intelligence allows autonomy, blurring the boundaries between the physical, the biological, and the digital spheres.

What does the sequence of Fig. 1.2 tell us? Industrial revolutions have been triggered by materials: flint, cast iron, steel, silicon. Material development is driven by industrial revolutions. The relationship is a close one, the synergies, great.

Dependence. The way we use materials has changed. “Use” is too weak a word—it sounds as if we have a choice: use, or perhaps not use? We don’t just “use” materials, we are totally dependent on them (Fig. 1.3). Over time this dependence has progressively changed from a reliance on renewable materials—the way humankind existed for thousands of years—to one on materials that consume

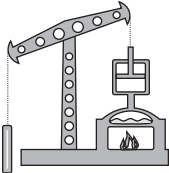
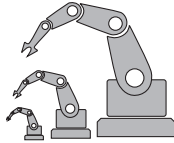
Industrial revolution	Characteristics	Enabling materials
0 	2.5 million years BCE - Tools - Changed subsistence patterns	- Wood - Stone, particularly flint - Bone, Shell, - Leather
1 	1760 onward - Water and steam power - Mechanization - Industrial growth	- Coal, water - Cast iron - Brass, Bronze
2 	1810 onward - Mass production - Electric power - Urbanization	- Oil - Steel - Rubber, Glass - Magnetic materials
3 	1960 onward - Digital control - Automation - Globalization	Polymers, - Silicon - Aluminum - Advanced alloys
4 	Today: Industry 4.0 - Connectivity, IoT - Autonomy - Big data - Artificial intelligence	Materials 4.0 - Electrical material - Optical materials - Magnetic material - Sensing materials - Actuating materials

FIGURE 1.2 The succession of revolutions that have changed the face of industry and of materials. IoT, Internet of things.

resources that cannot be replaced. The industrial revolutions that have driven this change demand materials with ever more functionality and with them the transition:

- from small-scale production to large;
- from materials that are widely available to those that are comparatively scarce;
- from products from which materials are easily recovered to those in which materials are inaccessible and widely dispersed.

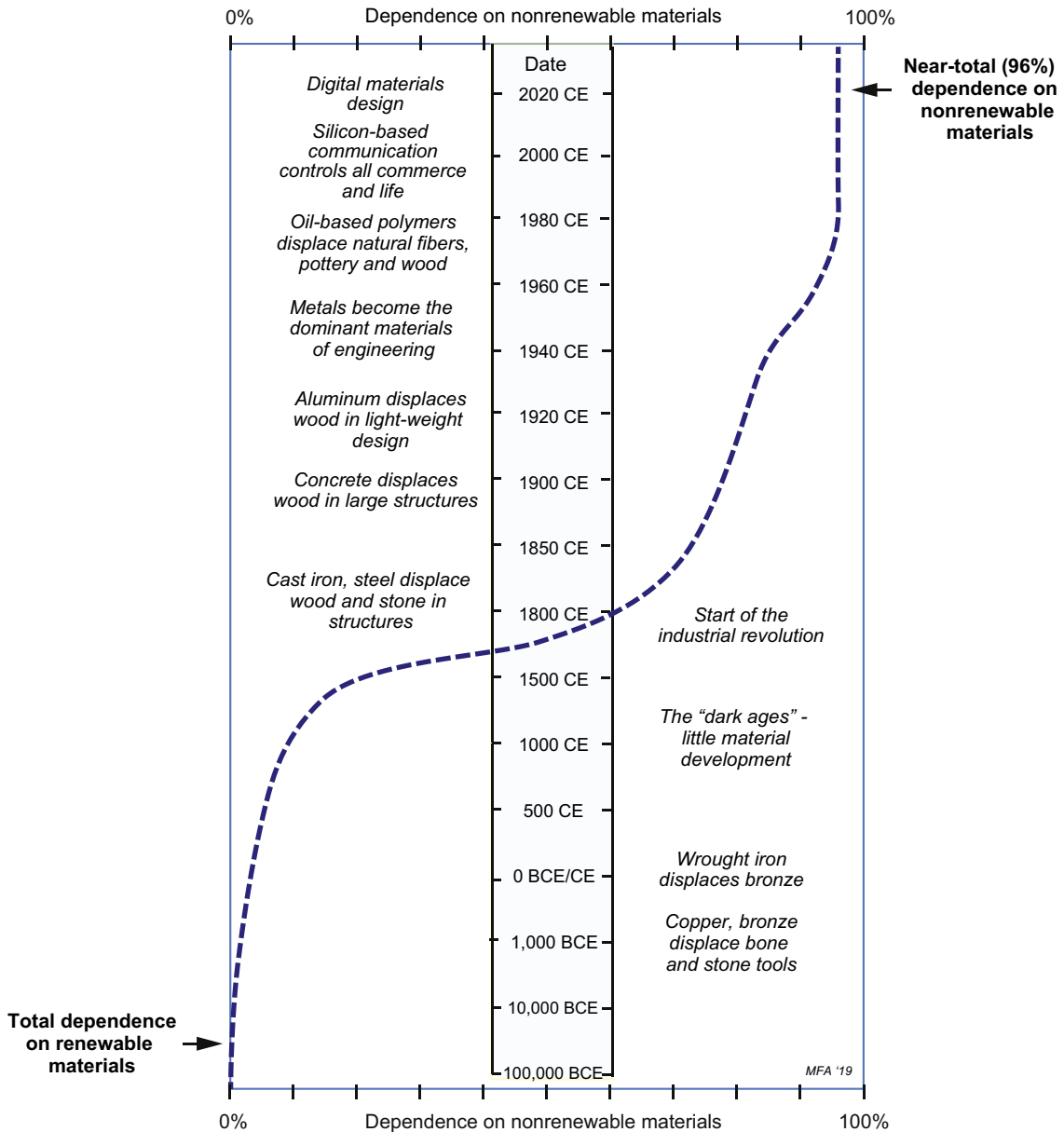


FIGURE 1.3 The increasing dependence on nonrenewable materials over time, rising to 96% today. Dependence is not a concern when resources are plentiful, but an emerging problem as they become scarce. (Data in part from USGS 2002.)

Dependence is dangerous; it is a genie in a bottle. Take away something on which you depend—meaning that you can't live without it—and life becomes difficult. Dependence exposes you to exploitation. While a resource is plentiful, market forces ensure that its price bears a relationship to the cost of its extraction. But the resources from which many materials are extracted—oil among them—are localized in relatively few countries. While these countries compete for buyers, the price remains geared to the cost of production. But if demand exceeds supply or the producing nations reach arrangements to limit it, the genie is out of the bottle. Think, for instance, of the price of oil, which today bears little relationship to the cost of producing it.

Dependence, then, is a condition to be reckoned with. We will encounter its influence in subsequent chapters.

Newsclip: “Resource use expected to double by 2050.”

International Resource Panel Report expects material resource use to reach nearly 90 billion tonnes in 2017 and more than double from 2015 to 2050.

United Nations Environment Programme, December 3, 2017

Newsclip: Has humanity's ecological footprint reached a peak?

Studies suggest that 86% of the world's population live in countries with an ecological deficit, meaning that the residents take more from nature than the country's ecosystems can regenerate. Wealthy nations buy themselves out of domestic resource deficiency, but 75% of humanity can't because they live in countries with both an ecological deficit and below-average income.

Global Footprint Network, April 9, 2018.

1.4 Materials and the environment

All human activity has some impact on the environment in which we live. The environment has some capacity to cope with this, so that a certain level of impact can be absorbed without lasting damage. But it is clear that current human activities exceed this threshold with increasing frequency, diminishing the quality of the world in which we now live and threatening the well-being of future generations. Part, at least, of this impact derives from the manufacture, use, and disposal of products, and products, that, without exception, are made from materials.

The materials consumption in the United States now exceeds 22 tonnes per person per year. The average level of global consumption is barely one-eighth of this but is growing twice as fast. The materials (and the energy needed to make and shape them) are drawn from *natural resources*: ore bodies, mineral deposits, fossil hydrocarbons. The earth's resources are not infinite, but until recently,

they have seemed so: the demands made on them by manufacture throughout the 18th, 19th, and early 20th centuries seemed infinitesimal, the rate of new discoveries always outpacing the rate of consumption. This perception has now changed. The realization that we may be approaching certain fundamental limits seems to have surfaced with surprising suddenness, but warnings that things can't go on forever are not new. Thomas Malthus,⁴ writing in 1798, foresaw the link between population growth and resource depletion, predicting gloomily that "the power of population is so superior to the power of the earth to produce subsistence for man that premature death must in some shape or other visit the human race." Almost 200 years later, in 1972, a group of scientists⁵ known as the Club of Rome reported their modeling of the interaction of population growth, resource depletion, and pollution, concluding that "if (current trends) continue unchanged ... humanity is destined to reach the natural limits of development within the next 100 years." The report generated both consternation and criticism, largely on the grounds that it did not allow for scientific and technological advance. But since 2010, thinking about this broad issue has reawakened. There is a growing acceptance that, in the words of the Brundtland⁶ Report, "many aspects of developed societies are approaching ... saturation, in the sense that things cannot go on growing much longer without reaching fundamental limits. This does not mean that growth will stop in the next decade, but that a declining rate of growth is foreseeable in the lifetime of many people now alive. In a society accustomed ... to 300 years of growth, this is something quite new, and it will require considerable adjustment."

These are long-term concerns. Of more immediate concern are the changes in climate, glaciation, and sea level caused by rising global temperatures, leading, in 1988, to the formation of the Intergovernmental Panel on Climate Change (IPCC).

The IPCC and its reports. The IPCC—an international study set up by the World Meteorological Organization and the United Nations Environmental Programme—publishes a series of reports on the effects of industrial activity on the biosphere and the human environment. The most recent of these as of this

⁴Thomas Malthus (1766–1834), English demographer and philosopher, is best known for his gloomy prognostication that population growth will always tend to outrun food supply. He was one of the first Fellows of the Society for Statistics, a tool that demographers have used ever since.

⁵Notably, Donella H. Meadows (1941–2001), American environmental scientist and lead author of *The Limits to Growth*, a book that reignited the debate about the limits of the earth's capacity to support human economic expansion. Meadows founded the Sustainability Institute, which combined research in global systems with practical demonstrations of sustainable living.

⁶Gro Harlem Brundtland (1939), three times prime minister of Norway, has also been director general of the World Health Organization and chair of the Brundtland Commission, which authored the Brundtland Report on sustainable development.

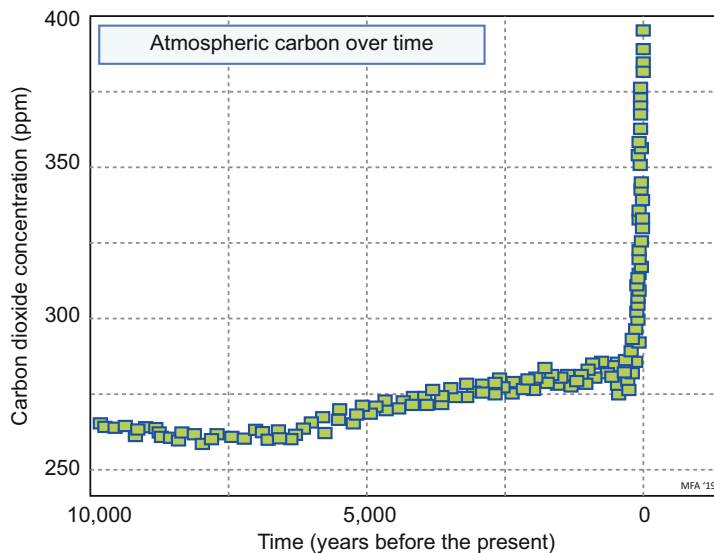


FIGURE 1.4 Atmospheric concentration of CO_2 over the past 10,000 years measured from ice cores and atmospheric samples.

writing, the sixth, appeared in 2017.⁷ Briefly, the conclusions it reaches are the following:

- The average air, ocean, and land-surface temperatures of the planet are rising. The increase is causing widespread melting of snow and ice cover, rising sea levels, and changes in climate.
- Climate change, measured, for instance, by the annual averages of the air, ocean, and land temperatures, affects natural ecosystems, agriculture, animal husbandry, and human environments. An increase in average global temperature of just 1°C can have a significant effect on all of them. Urgent action is needed to avoid a rise of 2°C . A rise of 5°C would be catastrophic.
- The global atmospheric concentration⁸ of CO_2 has increased at an accelerating rate since the start of the Industrial Revolution (around 1750) and is now at its highest level in the past 600,000 years. Most of the increase has occurred between 1950 and the present day (Fig. 1.4).

⁷<https://royalsociety.org/~media/policy/Publications/2017/27-11-2017-Climate-change-updates-report.pdf>.

⁸Throughout this book, carbon release into the atmosphere is measured in kilograms of CO_2 . One kilogram of elemental carbon is equivalent to 3.6 kg of CO_2 . For a wide range of materials the value of $\text{CO}_{2,\text{eq}}$ can be equated to $1.06 \times \text{CO}_2$, both measured in kg/kg.

- Increasingly accurate geophysical measurements allow the history of temperature and atmospheric carbon to be tracked, and increasingly precise meteorological models allow scenario exploration and prediction of future trends in both. Both suggest that the climate temperature rise is caused by greenhouse gases, and that anthropomorphic (human-made) CO₂ is the probable cause.

The causes of these concerns are complex, but at the bottom, one stands out: population growth. Examine, for a moment, [Fig. 1.5](#). It is a plot of the global population over the past 2000 years. It looks like a simple exponential growth (something we examine in more depth in Chapter 2), but it is not. Exponential growth is bad enough—it is easy to be caught out by the way it surges upward. But this is far worse. Exponential growth has a constant doubling time; if exponential, a population doubles in size at fixed, equal time intervals. The doubling times for global population are marked on the figure. For the first 1500 years it is constant, at about 750 years, but after that, starting with the industrial revolution, the doubling time halves, then halves again, and then again. This behavior has been called “explosive growth”; it is harder to predict and results in a more sudden change. Malthus and the Club of Rome may have had the details wrong, but it seems they had the principle right.

Global resource depletion scales with the population and with per-capita consumption. Per-capita consumption in developed countries is stabilizing, but that in the emerging economies, as already said, is growing more quickly. [Fig. 1.6](#) shows

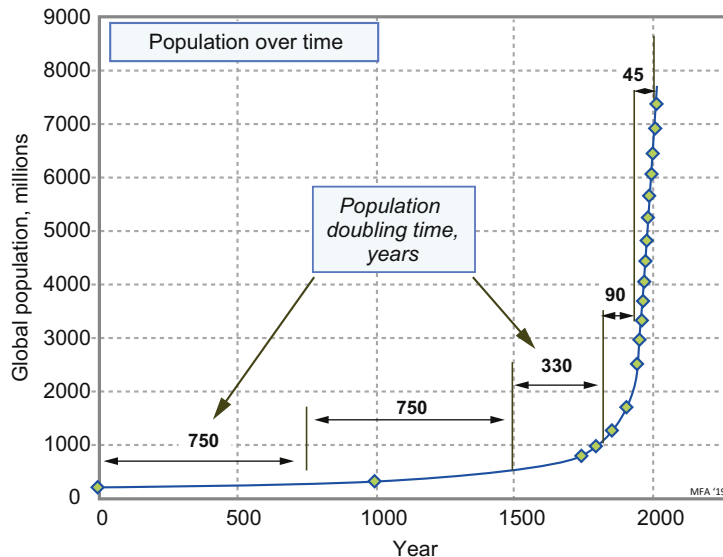


FIGURE 1.5 Global population growth over the past 2020 years, showing the doubling times.

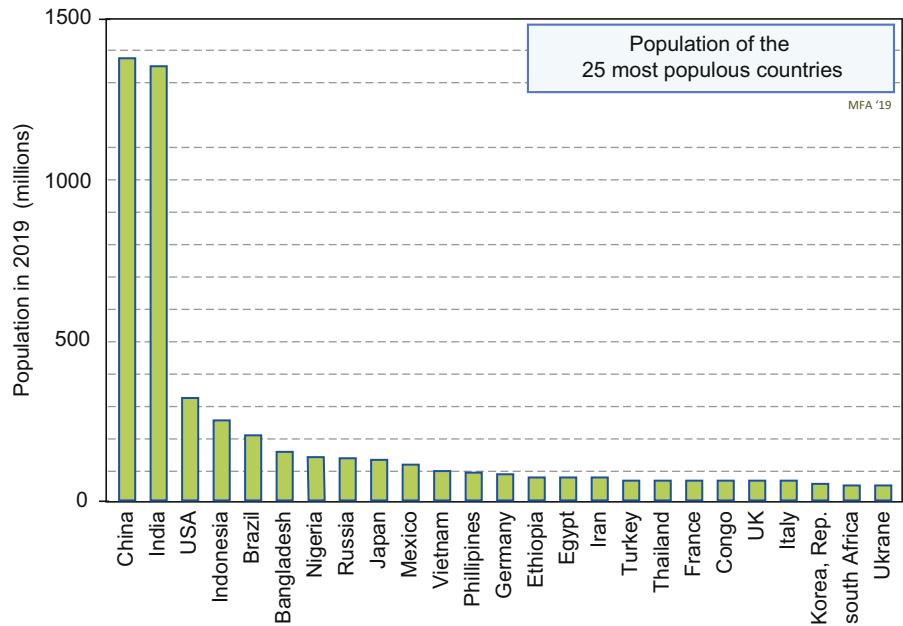


FIGURE 1.6 The populations of the 25 most populous developed and developing countries in 2018.

the distribution of population in the 25 most populous nations containing, between them, three-quarters of the global total. The first two—China and India—account for 37% of this total, and it is in these two that material consumption is growing most rapidly.

Given all this, it makes sense to explore the ways in which materials are used in design and how this might change as environmental prerogatives become increasingly pressing. The chapters that follow do that.

Newsclip: Population, affluence, and consumption. “Be a bull as China shops.”

The world’s largest population is enjoying rising wages and a growing disposable income. In short: 1.3 billion people are becoming active consumers

The Times, May 21, 2011

Newsclip: Overpopulated and underfed. Countries near a breaking point.

Over-population drives mass migration, starvation and civil unrest. The population crisis is especially acute in Africa, but it spans the globe from Central America to Asia.

New York Times, June 15, 2017

Newsclip: (Voracious consumption) × (rising population) = planetary crisis.

Marcus Neale of the UN Climate Change Adaptation Unit warns that over-population coupled with over-consumption is a toxic combination.

***The Guardian*, July 24, 2018**

No further comment needed

1.5 Summary and conclusions

H. sapiens—that means us—differs from all other species by its competence in making things out of materials. We are not alone in the ability to *make*: termites build towers, birds build nests, beavers build dams; all creatures, in some way, make things. The difference lies in the *competence* demonstrated by humans and in their extraordinary (there can be no other word) ability to expand and adapt that competence by research and development.

The timeline of Fig. 1.1 illustrates this expansion. There is a tendency to think that progress of this sort started with the Industrial Revolution, but knowledge about and development of materials has a longer and more continuous history than that. The misconception arises because of the bursts of development in the 18th, 19th, and 20th centuries, forgetting the technological developments during the great eras of the Egyptian, Chinese, Greek, and Roman empires, not just to shape stone, clay, and wood, and to forge and cast copper, tin, and lead, but also to find and mine the ores and to import them over great distances.

The import of tin from a remote outpost of the Roman empire (Cornwall, England, to Rome, Italy, 3300 km by sea) to satisfy the demands of the Roman State hints at an emerging material dependence. The dependence has grown over time with the deployment of ever more human-made materials, until today it is almost total. In reading this text, then, do so with the perspective that materials, our humble servants throughout history, have become, in another sense, our masters.

1.6 Further reading

- Delmonte, J. (1985) “Origins of materials and processes”, Technomic Publishing Company, Pennsylvania, USA. ISBN 87762-420-8. (*A compendium of information about materials in engineering, documenting the history.*)
- Flannery, T. (2010) “Here on earth”, The Text Publishing Company, Victoria, Australia. ISBN 978-1-92165-666-8. (*The latest of a series of books by Flannery documenting man’s impact on the environment.*)
- Hamilton, C. (2010) “Requiem for a species: why we resist the truth about climate change” Allen and Unwin, NSW, Australia. ISBN 978-1-74237-210-5. (*A profoundly pessimistic view of the future for mankind.*)

- Kent, R. (2009) "Plastics timeline", <http://www.historyofplastic.com/plastic-history/plastic-timeline/> (A web site devoted, like that of Material Designs, to the history of plastics.)
- Lomberg, B. (2010), editor, "Smart solutions to climate change: comparing costs and benefits", Cambridge University Press, Cambridge UK. ISBN 978-0-52113-856-7. (A multi-author text in the form of a debate ("The case for ...", "The case against...") covering climate engineering, carbon sequestration, methane mitigation, market and policy-driven adaptation.)
- Lovelock, J. (2009) "The vanishing face of Gaia", Penguin Books, Ltd. London, UK. ISBN 978-0-141-03925-1. (James Lovelock reminds us that humans are just another species, and that species have appeared and disappeared since the beginnings of life on earth.)
- Makin Metal Powders Co. (2018) "History of metals timeline" (An infographic displaying the history of the discovery of metals. See Kent and Materials Designs in this reference list for plastics time-lines.) <http://www.makin-metals.com/about/history-of-metals-infographic/>.
- Malthus, T. R. (1798), "An essay on the principle of population", London, Printed for Johnson, St. Paul's Church-yard. <http://www.ac.wvu.edu/~stephan/malthus/malthus>. (The originator of the proposition that population growth must ultimately be limited by resource availability.)
- Material Designs (2011) "A timeline of plastic", <http://materialdesigns.wordpress.com/2009/08/06/a-timeline-of-plastics/>. (A web site devoted, like that of Kent, to the history of plastics.)
- Meadows D.H., Meadows D.L., Randers J, and Behrens W.W., (1972) "The limits to growth", Universe Books, New York. (The "Club of Rome" report that triggered the first of a sequence of debates in the 20th century on the ultimate limits imposed by resource depletion.)
- Meadows, D.H., Meadows, D.L. and Randers, J. (1992) "Beyond the limits", Earthscan, London, UK. ISSN 0896-0615. (The authors of "The Limits to Growth" use updated data and information to restate the case that continued population growth and consumption might outstrip the Earth's natural capacities.)
- Nielsen, R. (2005) "The little green handbook", Scribe Publications Pty Ltd., Carlton North, Victoria, Australia. ISBN 1-920769-30-7. (A cold-blooded presentation and analysis of hard facts about population, land and water resources, energy and social trends.)
- Plimer, I. (2009) "Heaven and Earth – Global warming: the missing science", Connor Publishing, Ballam, Victoria, Australia. ISBN 978-1-92142-114-3. (Ian Plimer, Professor of Geology and the University of Adelaide, examines the history of climate change over a geological time-scale, pointing out that everything that is happening now has happened many times in the past. A geo-historical perspective, very thoroughly documented.)

- Schmidt-Bleek, F. (1997) "How much environment does the human being need – factor 10 – the measure for an ecological economy", Deutscher Taschenbuchverlag, Munich, Germany. ISBN 3-936279-00-4. *(Both Schmidt-Bleek and von Weizsäcker, referenced below, argue that sustainable development will require a drastic reduction in material consumption.)*
- Thompson, R. and Thompson M. (2016) "Sustainable materials, processes and production", Thams and Hudson, ISBN 978-0-500-29071-2. *(A beautifully illustrated guide to renewable materials, their processing and recycling.)*
- USGS (2002) Circular 2112 "Materials in the economy – material flows, scarcity and the environment", by L.W. Wagner, US Department of the Interior (www.usgs.gov). *(A readable and perceptive summary of the operation of the material supply chain, the risks to which it is exposed, and the environmental consequences of material production.)*
- von Weizsäcker, E., Lovins, A.B. and Lovins, L.H. (1997) "Factor four: doubling wealth, halving resource use", Earthscan publications, London, UK. ISBN 1-85383-406-8; ISBN-13: 978-1-85383406-6. *(Both von Weizsäcker and Schmidt-Bleek, referenced above, argue that sustainable development will require a drastic reduction in material consumption.)*

1.7 Exercises

E1.1. Material history. Use Google to research the history and uses of one of the following materials:

- tin
- glass
- cement
- Bakelite
- titanium
- carbon fiber

Present the result as a short report of about 100–200 words (roughly half a page). Imagine that you are preparing it for schoolchildren. Who used it first? Why? What is exciting about the material? Do we now depend on it or could we, with no loss of engineering performance or great increase in cost, live without it?

E1.2. Ecological footprint. The caption for the cover image of this chapter mentions the "ecological footprint." Sounds important, but what is it? What units are used to measure it? What do these units mean? Use the Internet to find out.

E1.3. Materials and energy. There is international agreement that it is desirable (essential, in the view of some) to reduce global energy consumption. Producing materials from ores and feedstocks requires energy (its "embodied energy"). The table lists the energy per kilogram and the

annual consumption of five materials of engineering. If consumption of each could be reduced by 10%, which material offers the greatest global energy saving? Which the least?

Material	Embodied energy (MJ/kg)	Annual global consumption (tonnes/year)
Steels	29	1.1×10^9
Aluminum alloys	200	3.2×10^7
Polyethylene	80	6.8×10^7
Concrete	1.2	1.5×10^{10}
Device-grade silicon	Approximately 2000	5×10^3

E1.4. Productive land per capita. The ultimate limits of most resources are difficult to assess precisely, although estimates can be made. One resource, however, has a well-defined limit: that of usable land area. The surface area of the globe is 511 million km², or 5.11×10^{10} ha (a hectare is 0.01 km²). Only a fraction of this is land, and only part of that land is useful—the best estimate is that 1.1×10^{10} ha of the earth’s surface is biologically productive. Industrial countries require 6 ha of biologically productive land per head of population to support current levels of consumption. The current (2019) global population is close to 7.7 billion (7.7×10^9).

- (1) What is the current biologically productive land area per person if it were equally shared?
- (2) How does this compare with the ecological footprint of an industrialized country?
- (3) What conclusions can you draw?

Nation	DMC (tonnes/year/capita)	GDP (USk\$/year/capita)
Denmark	23.5	53
France	11	37
Germany	15.5	42
Greece	11	19
Italy	8.5	31
Luxembourg	25	99
Slovakia	13	17
Spain	8.5	27
Sweden	23	52
UK	9	40
USA	23	58

DMC, domestic material consumption; GDP, gross domestic product.

E1.5. Material consumption. The domestic material consumption (DMC) per capita is the total amount of material directly used in an economy and equals direct material input minus exports.⁹ Is there a correlation between DMC and gross domestic product (GDP)? The table lists 2017 data for the DMC and GDP for a number of developed nations. Plot one against the other to explore the relationship.

China has a DMC of 29 and a GDP per capita of 0.8. Add it to the plot. Can its position be explained?

⁹https://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=t2020_r1110.

Resource consumption and its drivers

CONTENTS

- 2.1 Introduction and synopsis
- 2.2 Where do materials come from?
- 2.3 Resource consumption
- 2.4 Exponential growth and doubling times
- 2.5 Summary and conclusions
- 2.6 Further reading
- 2.7 Exercises



The Bingham Canyon copper mine in Utah, now 1.2 km deep and 4 km across, and a Caterpillar truck that is part of the excavation equipment. Images courtesy of Kennecott Utah Copper.

2.1 Introduction and synopsis

You can't reach robust conclusions about humanity's influence on the environment without a feel for the numbers.¹ As we saw in Chapter 1, manufacturing today is addictively dependent on continuous flows of materials and energy. How big are these? A static picture—that of the values today—is a starting point, and the quantities are enormous. And, of course, they are *not* static. Growth is the lifeblood of today's consumer-driven economies. An economy that is not growing is "faltering," "stagnant," "sick" (words use by economics correspondents of *The Times*). Business enterprises, too, seem to need to grow to survive. And all this growth causes the consumption of materials and energy to rise, or at least it has done so until now. Growth can be linear, increasing at a constant rate. It can be exponential, increasing at a rate proportional to its current size. Or, as we saw in Chapter 1, it can sometimes increase even faster than that.

This chapter is about *orders of magnitude*: the round numbers describing the amounts of stuff we consume and the rate at which it grows. Exponential growth plays nasty tricks. Something cute and cuddly, growing exponentially, eventually evolves into an oppressive monster. Exponential growth is characterized by a doubling time: anything growing exponentially doubles its size at regular, equal intervals. Money invested in fixed-rate bonds has a doubling time, though it is usually a long one. The consumptions of natural resources—minerals, energy, water—grow in a roughly exponential way: they, too, have doubling times, and some of these are short. Certain resources are so abundant that there is no concern that we are using them faster and faster: the mineral resources from which iron and aluminum are drawn are examples. But others are not so abundant: their ores are localized and the amount that is economically accessible is limited. Then the doubling-up nature of exponential growth becomes a concern: consumption of these cannot continue to double forever. And extracting and processing any material, whether plentiful or scarce, uses energy—lots of energy—and it too is a resource under duress.

This sounds alarming, and many alarming statements have been made about it. But consider this: in 1930, the exhaustion time for the reserves of copper ore was estimated to be 30 years. Today, 80 years later, the exhaustion time of copper reserves is calculated as ... 30 years. There is something going on here other than exponential growth. This chapter explores it.

First, however, a quick look at what the earth has to offer.

2.2 Where do materials come from?

We have 92 usable elements. Most of them are metals. If we want them for engineering purposes, we have to mine the naturally occurring minerals in which

¹Appendix A at the end of this book contains data for the engineering properties of materials. Appendix B contains data for their eco-related properties.

they are found, mostly as oxides, sulfides, or carbonates. They come mixed with other stuff, from which they have to be separated before the metal can be extracted. The mining, separating, and extracting all take energy. The more dilute the ore, the more stuff has to be dug, the greater the effort of separation, and the greater the energy demand.

Fig. 2.1 shows the abundance of elements in the earth's crust. They differ by a factor of 10^{10} . The most abundant are the "rock-making" elements calcium, silicon, aluminum, and magnesium. The eight elements that lie at the top of the figure account for over 98% of the total—no others have a concentration above 0.1%. The "precious" metals (yellow bars on the figure) all lie below 0.00001%, the value for silver. The concentration of iridium is 10,000 times smaller than that. The earth's oceans, too, contain elements (Fig. 2.2), but here, except for sodium and magnesium, the concentrations are even smaller.

The metal content of the ore is called the *ore grade*, G , measured as the tonnes of metal per tonne of ore as mined. Very approximately, the cost C_m (\$/kg) of extracting metals scales inversely with the ore grade G (%), such that:

$$C_m \approx \frac{10}{G}. \quad (2.1)$$

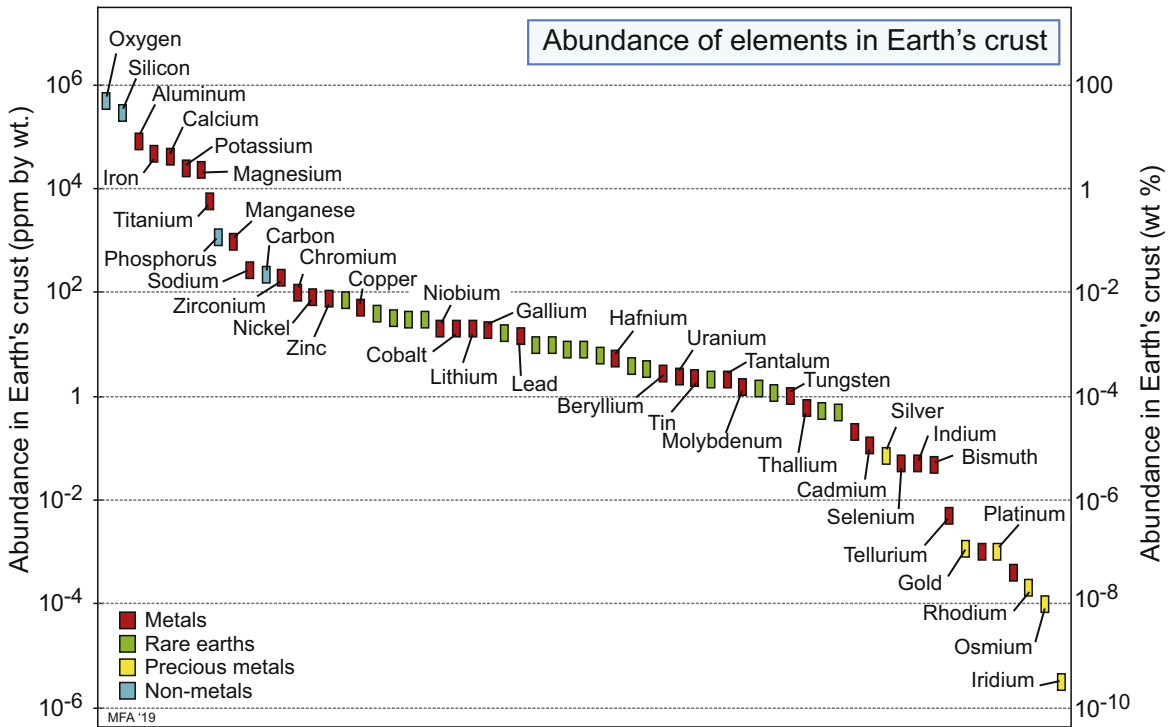


FIGURE 2.1 The average concentration of the elements in the earth's crust, as parts per million (ppm) and as wt%. The top eight elements account for 98.5% of the total.

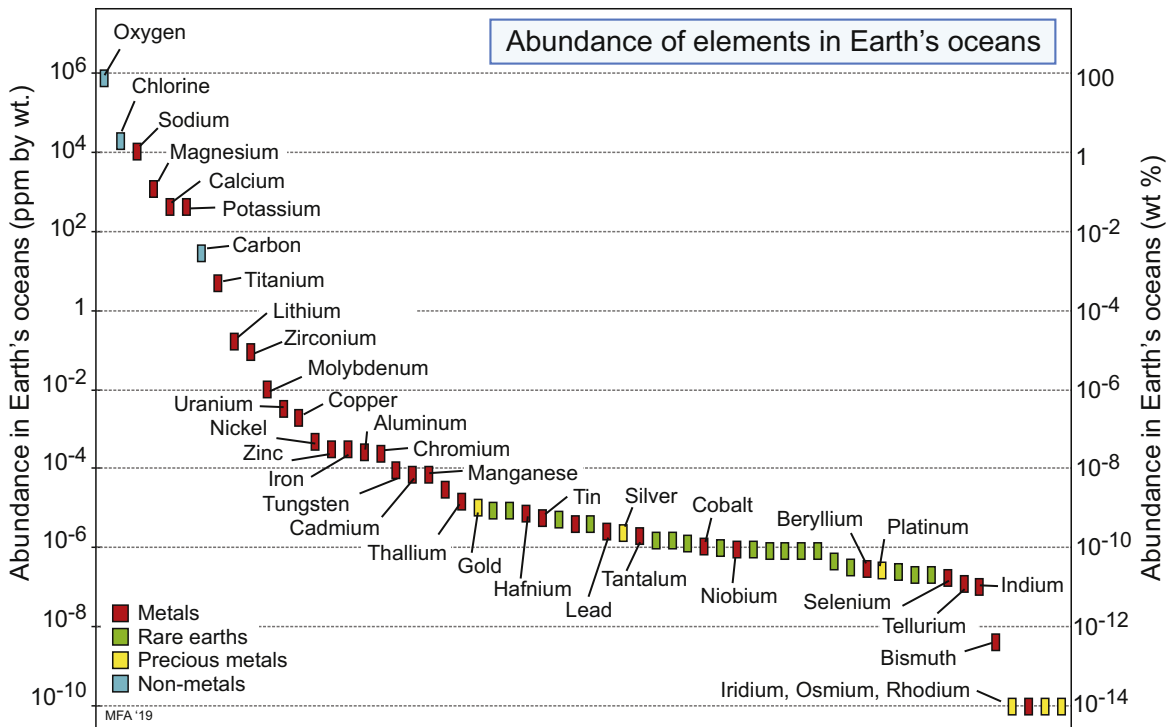


FIGURE 2.2 The average concentration of the elements in the earth's oceans, as parts per million (ppm) and as wt%. Most are too dilute to allow for economic recovery.

If copper, as an example, had to be extracted from ore with a grade equal to its average concentration (50 ppm) in the crust, what might it cost? It would cost \$2000/kg, according to Eq. (2.1). In reality it costs less than one-hundredth of that (at this writing, July 1, 2019, copper costs \$5.97/kg). The difference, of course, is that copper is not mined from the *average* crust but from localized, copper-rich deposits.

How do mineral-rich deposits form? At least four different processes, all very slow, are at work:

- Volcanism distills out the lower-melting minerals and vaporizes the more volatile ones, condensing them again as they cool (natural thermochemistry).
- Erosion by water and wind grinds down the crust, sweeping the debris to calmer places where the heavier components settle more quickly than the lighter ones (gravimetric chemistry).
- Water dissolves water-soluble minerals in a way controlled by its pH, dumping the dissolved minerals when they are concentrated by evaporation (hydrochemistry).

- Natural organisms are effective concentrators of minerals; the coal, oil, and gas deposits reflect the ability of plant life to concentrate carbon, and some phosphate deposits are the accumulated guano of birds and bats (biochemistry).

These treasure troves are the resources we draw on today. All four took a long time to form. We use them far faster than they can be re-created, forcing us to mine ever leaner, low-*G* ores. Improved extraction technology allows lower-grade ores to be exploited, but, as [Eq. \(2.1\)](#) says, the lower the grade, the higher the cost.

With that background, we now turn to consumption.

2.3 Resource consumption

Materials. Speaking globally, we consume roughly 20 billion (10^{10}) tonnes of engineering materials per year, an average of 2.7 tonnes per person. [Fig. 2.3](#) gives a perspective: it is a bar chart of the primary production of the materials used in the greatest quantities. It has some interesting messages. On the extreme left, for calibration, are hydrocarbon fuels—oil and coal—of which we currently consume a colossal 9 billion (9×10^9) tonnes per year. Next, moving to the right, are metals. The scale is logarithmic, making it appear that the production of steel (the first metal) is only a little greater than that of aluminum (the next); in reality, the production of steel exceeds, by a factor of 10, that of all other metals combined. Steel may lack the high-tech image that attaches to materials like titanium, carbon-fiber-reinforced composites, and (most recently) nanomaterials, but make no mistake, its versatility, strength, toughness, low cost, and wide availability are unmatched. At the other extreme are the platinum-group metals and the rare earths (15 elements near the bottom of the periodic table). Their quantities are small, but their importance is large. We return to them in later chapters.

Polymers come next. Fifty years ago, their production was tiny. Today the production, in tonnes per year, of the five commodity polymers polyethylene (PE), poly(vinyl chloride), polypropylene, polystyrene, and polyethylene terephthalate is comparable to that of aluminum; if measured in cubic meters per year, they approach that of steel. The really big ones, though, are the materials of the construction industry. Steel is one of these, but the production of wood for construction purposes exceeds even that of steel when measured in tonnes per year (as in the diagram), and since it is a factor of 10 lighter, wood totally eclipses steel when measured in cubic meters per /year. Bigger still is the production of concrete, which exceeds that of all other materials combined. The other big ones are asphalt (roads), cement (most of which goes into concrete), brick, and glass. Fibers, too, are produced in very great quantities. Natural fibers have played a role in human life for tens of thousands of years, and continue to do so, but synthetic fibers now surpass them. The last column shows woods and fibers, including glass and carbon. In the 1990s, carbon fiber would not have crept onto the bottom of this chart. Today its production is approaching that of titanium and is growing much more quickly.

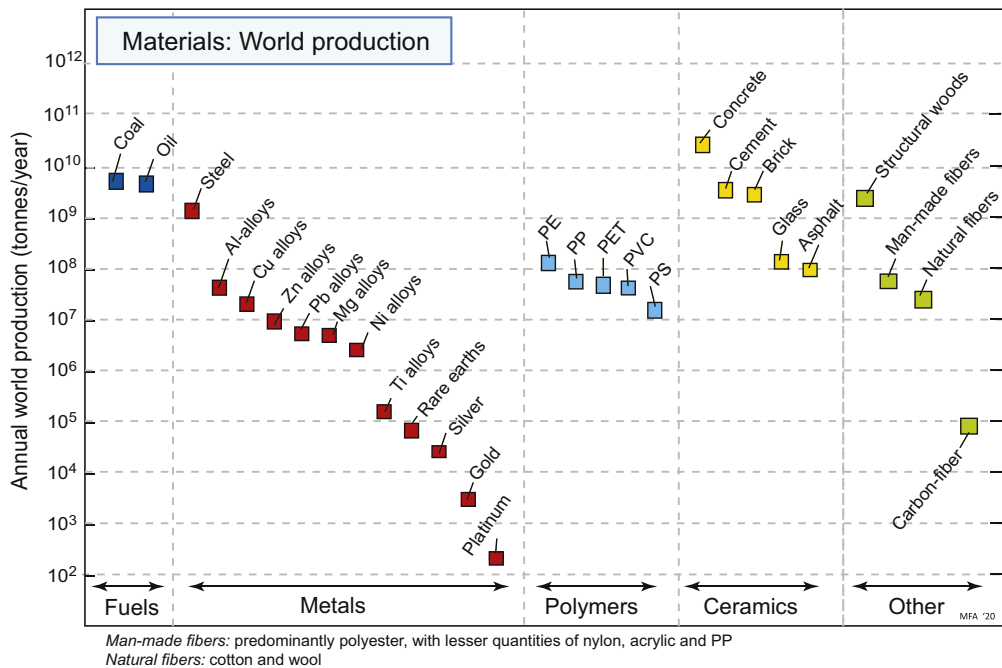


FIGURE 2.3 The annual world production of 27 materials on which industrialized society depends. The scale is logarithmic. The log scale conceals the great differences; the production of steel, for instance, is 1 billion (10^9) times larger than that of platinum. PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PS, polystyrene; PVC, poly(vinyl chloride).

Energy. Although this book is about materials, energy appears throughout; it is inseparable from the making of materials, their manufacture into products, their use, and their ultimate disposal. The SI unit of energy is the joule (J), but because a joule is very small, we generally use kJ (10^3 J), MJ (10^6 J), or GJ (10^9 J) as the unit. Power is joules/s, or watts (W), but a watt, too, is small, so we usually end up with kW, MW, or GW. The everyday unit of electrical energy is the kWh, meaning 1 kW drawn for 3600 s, so 1 kWh = 3.6 MJ.

Where does energy come from? There are ultimately just four sources:

- the sun, which drives the wind, wave, hydro, and photoelectric phenomena and the photochemical processes that give biomass;
- the moon, which drives the tides;
- nuclear decay of unstable elements inherited from the creation of the earth, providing geothermal heat and nuclear power; and
- hydrocarbon fuels, the sun's energy in fossilized form.

Harvesting these and the implications for materials of doing so are the subjects of Chapter 12. For now we just note that, while all four are ultimately finite, the time scale for the exhaustion of the first three is so large that it is safe to regard them as infinite.

How much energy do we use in a year? When speaking of world consumption, the unit of convenience is the exajoule, symbol EJ, a billion billion (10^{18}) joules.² The value in 2018 was about 570 EJ/year and, of course, it is rising. Fig. 2.4 shows where it comes from. Fossil fuels dominate the picture, providing about 82% of the total (Fig. 2.5A). Nuclear energy gives about 8%. Renewables—hydro, wind, wave, biomass, solar heat, and photovoltaics—add up to another 10%. These sun-driven energy pools are enormous, but unlike fossil and nuclear fuels, which are concentrated, they are distributed, making them hard to harvest.

Where does this energy go? Most of it goes into three big sectors: transport, domestic and commercial buildings, and industry—including that of materials production (Fig. 2.5B). Making materials consumes about 15% of global energy and is responsible for about the same fraction of carbon emitted to the atmosphere.

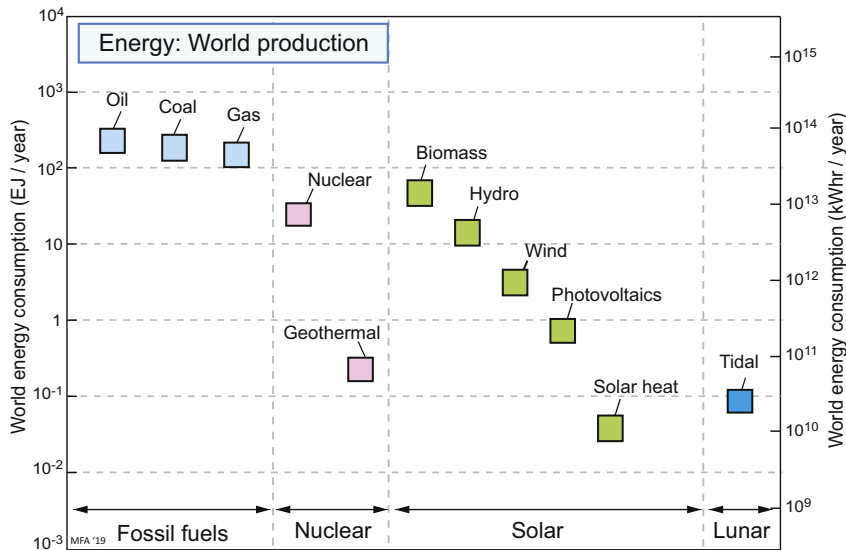


FIGURE 2.4 The annual world consumption of energy by source. The units on the left are exajoules (10^{18} J); those on the right are the more familiar kilowatt-hours. Sources: BP (2018), IRENA (2018).)

²1 TWh = 10^9 kWh = 3.6×10^{15} J = 0.0036 EJ = 86.2 tonnes oil equivalent.

Example: the energy demands of steelmaking. The world production of steel in 2017 was 1700 million tonnes. The embodied energy of steel is approximately 31 MJ/kg. The annual global consumption of energy is 570 EJ. What fraction of the world's annual energy is required to provide the steel we consume?

Answer. The annual energy embodied in steels is $1.7 \times 10^9 \times 1000 \times 31 \times 10^6 = 5.3 \times 10^{19} \text{ J} = 34 \text{ EJ}$. This is 9% of global energy consumption.

Figs. 2.4 and 2.5A focus on the *sources of energy*. For the energy to be useful you have to do something with it, and that, almost always, involves *energy conversion* (Fig. 2.6). Almost always, conversion involves energy “losses.” The first law of thermodynamics says that energy is conserved, so it can’t really be lost. In almost all energy conversion some energy is converted to heat. *High-grade heat* is heat at high temperature, as in the burning gas of a power station—it can be used to do work. *Low-grade heat* is heat at low temperature and it is not nearly so useful; indeed most of it is simply allowed to escape, and in this sense, it *is* lost. Energy conversion generally has low-grade heat as a by-product with the result that the conversion efficiency, η , to *useful* energy is less than 100%. The refining of metals from their ores or the synthesis of polymers, for instance, involves the conversion of thermal or electrical energy into chemical energy. The conversion efficiency in material production is low, typically 5%–35%.

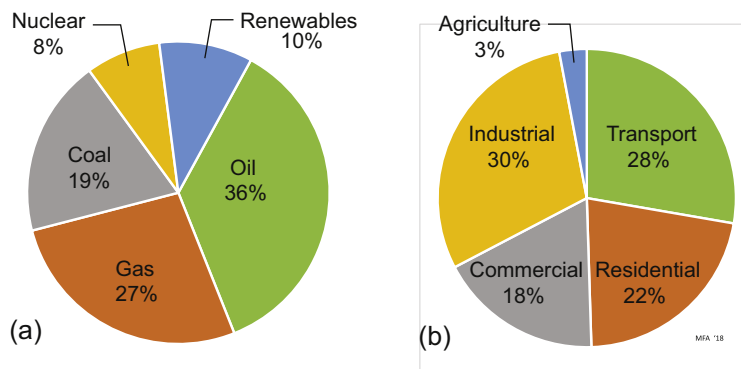


FIGURE 2.5 World energy consumption (A) by source and (B) by use. The nonrenewable carbon-based fuels oil, gas, and coal account for 82% of the total (US Energy Information Administration).

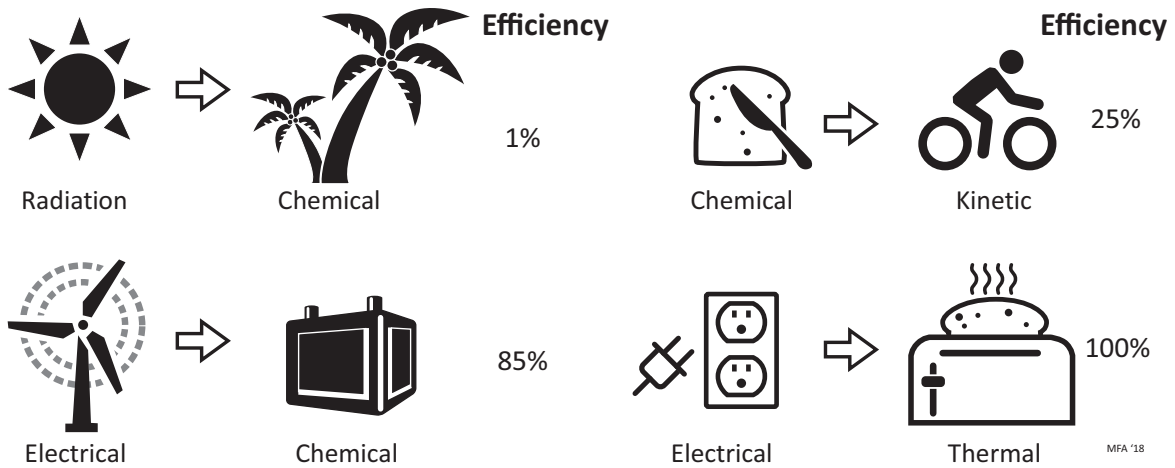


FIGURE 2.6 Examples of energy conversion. The efficiencies differ greatly.

Example: material process efficiencies. Fig. 2.7 shows the chain of energy-conversion steps in powering a hydraulic press. What is the overall conversion efficiency of the chain?

Answer. The overall efficiency $\eta_{tot} = 0.97 \times 0.38 \times 0.9 \times 0.85 \times 0.9 \times 0.35 = 0.1$. Ninety percent of the primary energy is lost as low-grade heat, performing no useful function.

Water. The third resource on which we depend is water. How much have we got? A great deal, but 97% of it is salt and two-thirds of the rest is ice (Fig. 2.8). Water is a renewable resource but only at the rate that the ecosystem allows. The worldwide demand for water has tripled since 1970³; forecasts suggest that more than half the human race will be short of it by 2050. Agriculture is the largest consumer, taking about 65% of all fresh water (Fig. 2.9). Industry consumes about 10% of the total. Energy supply depends on water, water supply on energy (Table 2.1). The interdependency of water and energy (the “water–energy nexus”) is set to intensify in the coming years, with significant implications for both energy and water security.

The water demands of materials and manufacture are measured directly as factory inputs and outputs. The production of steel, for example, uses water in the extraction of the minerals (iron ore, limestone, and fossil fuels), for material conditioning (dust suppression), for pollution control (scrubbers to clean up waste gases), and for cooling equipment and quenching ingots. Water consumption is measured as liters of water per kilogram of material produced, L/kg (or, equivalently, kg/kg,

³<https://www.statista.com/statistics/216527/global-demand-for-water/>.

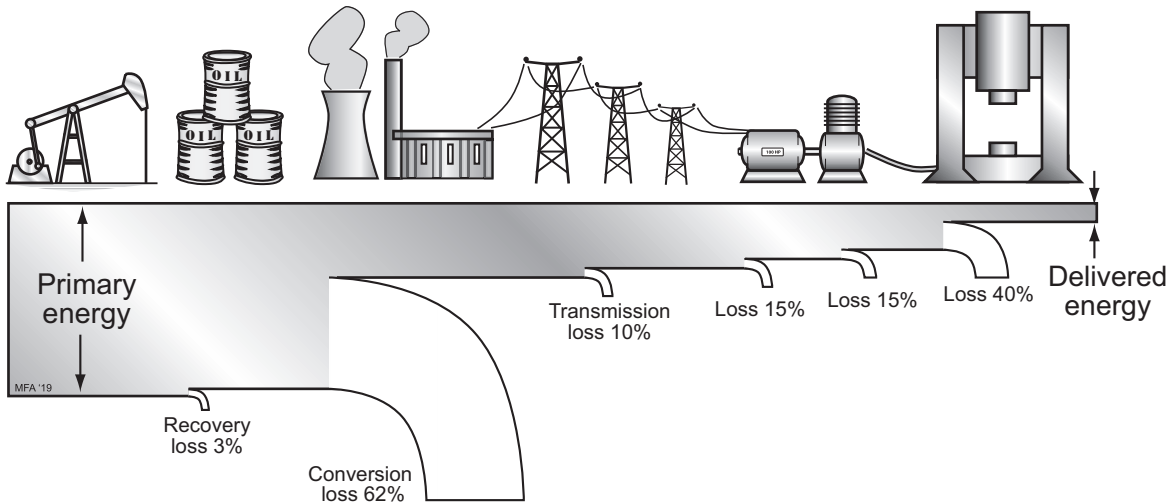


FIGURE 2.7 A chain of energy conversion and transmission steps, each with a “loss” of energy as low-grade heat.

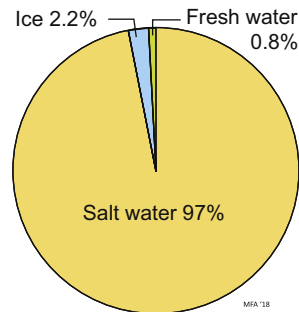


FIGURE 2.8 Global water distribution. Only a tiny fraction is accessible as fresh water.

since a liter of water weighs 1 kg). That for engineering materials ranges from 10 to over 1000 L/kg.

The water consumption for the growth of natural materials (biomass) requires a distinction between those that are irrigated and those that are not. Plants that are the source of wood, bamboo, cork, and paper are not usually irrigated; plants used to make bio-plastics (cellulose polymers, polylactides, starch-based thermoplastics) and for cattle feed (for leather) usually are. Recognizing this, water usage is reported in two ways: as commercial usage and as total usage. For most materials (metals, for instance) the two values are the same, but for trees and other plants the total usage includes nonirrigation water but the commercial usage does not. The data in Appendix B are for commercial water usage.

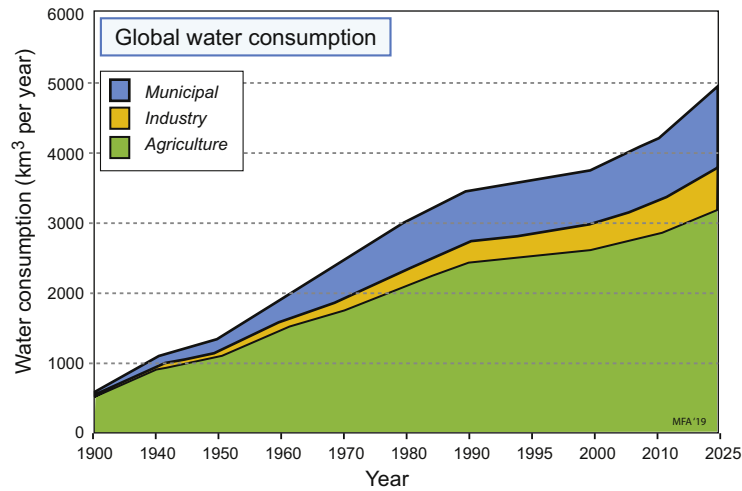


FIGURE 2.9 Global water consumption. Energy accounts for half of the yellow “industry” band. The other half includes material production.

Table 2.1 Approximate water demands of energy and energy demands of water⁴

Energy source	Water demand (m ³ /GJ)	Water source	Energy demand (MJ/m ³)
Grid electricity	24	Groundwater abstraction	1
Industrial electricity	11	Surface-water abstraction	0.2
Energy direct from coal	0.35	Groundwater treatment	0.01
Energy direct from oil	0.3	Surface-water treatment	0.1
Solar	0.3	Distribution	0.8
Wind	0.001	Desalination, reverse osmosis	15

2.4 Exponential growth and doubling times

Modern industrialized nations depend on a steady supply of raw materials. Demand for most increases at a rate that is growing exponentially with time, driven by increasing population and affluence. What does “exponential growth” mean? And what are its consequences?

⁴<https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExcerptWaterEnergyNexus.pdf>.

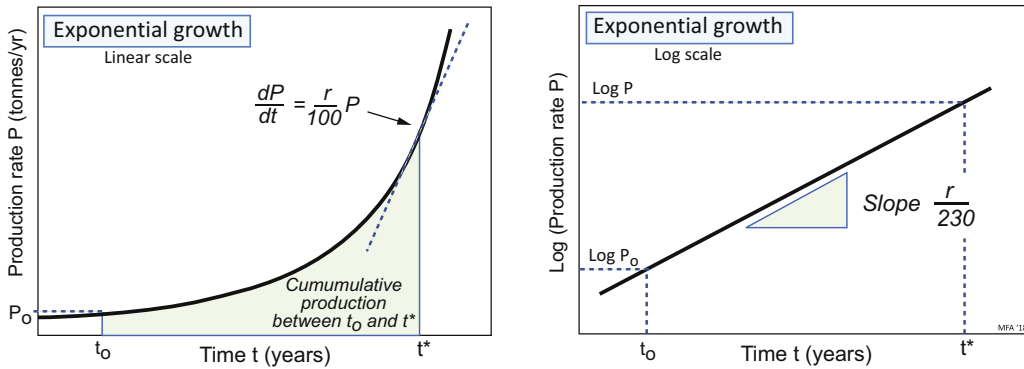


FIGURE 2.10 Exponential growth. Production P doubles in a time $t_d \approx 70/r$, where $r\%$ per year is the annual growth rate.

If the current rate of production of a material is P tonnes per year and this increases by a fixed fraction $r\%$ every year, then:

$$\frac{dP}{dt} = \frac{r}{100} P. \quad (2.2)$$

Integrating over time t gives:

$$P = P_0 \exp\left\{\frac{r(t - t_0)}{100}\right\}, \quad (2.3)$$

where P_0 is the production rate at time $t = t_0$. The left part of Fig. 2.10 shows how P grows at an accelerating rate with time. Taking logs of Eq. (2.3) gives:

$$\ln\left(\frac{P}{P_0}\right) = 2.3 \log_{10}\left(\frac{P}{P_0}\right) = \frac{r}{100}(t - t_0), \quad (2.4)$$

or $\log_{10}(P) = \log_{10}(P_0) + \frac{r}{230}(t - t_0)$,

so a plot of $\log_{10}(P)$ against time t , as in the right-hand side of Fig. 2.10, is linear with a slope of $r/230$.

Example: calculating growth rates. World production of silver in 1950 was 4000 tonnes. By 2010 it had grown to 21,000 tonnes. Assuming exponential growth, what is the annual growth rate of production of silver?

Answer. Exponential growth of production P is described by Eq. (2.4). Setting $P = 21,000$ tonnes per year, $P_0 = 4000$ tonnes per year, and $(t - t_0) = 60$ years, then solving for the growth rate r gives:

$$r = \frac{100}{(t - t_0)} \ln\left(\frac{P}{P_0}\right) = 2.8\% \text{ per year.}$$

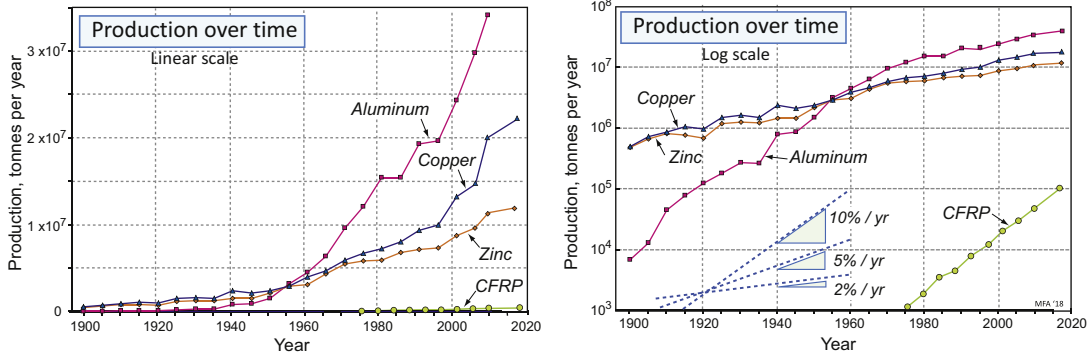


FIGURE 2.11 The growth of production of three metals and of CFRP (carbon-fiber reinforced polymers) over a 100-year interval, plotted on linear and semilogarithmic scales.

Fig. 2.11 shows the production of three metals and of carbon-fiber-reinforced polymers (CFRP) over the past 100 years, plotted, left, on linear scales and, right, on semilog scales, exactly as in the previous figure. The broken lines show the slopes corresponding to growth at $r = 2\%$, 5% , and 10% per year. Copper and zinc production has grown at a consistent 3% per year over this period. Aluminum, initially, grew at nearly 7% per year, but has now settled back to about $3\frac{1}{2}\%$. CFRP production is growing at 12% per year.

Exponential growth is characterized by a *doubling-time* t_D , over which production doubles in size. Setting $P/P_o = 2$ in Eq. (2.5) gives:

$$t_D = \frac{100}{r} \ln(2) \approx \frac{70}{r}. \quad (2.5)$$

At a growth rate of 10% per year, CFRP production doubles every 7 years.

Example: predicting future growth rates. The production of carbon fiber for structural use is growing exponentially at 12% per year. If the production in 2018 was 10^5 tonnes, what will it be in 2030?

Answer. Inserting the data into Eq. (2.4) of the text gives:

$$P = P_o \exp \frac{r}{100} (t - t_o) = 10^5 \exp(0.12 \times 12) = 4.2 \times 10^5 \text{ tonnes per year.}$$

CFRP production will increase by a factor of 4 by 2030.

The cumulative production Q_t between times t_o and t^* is found by integrating Eq. (2.4) over time, giving:

$$Q_t = \int_{t_o}^{t^*} P dt = \frac{100 P_o}{r} \left(\exp \left\{ \frac{r(t^* - t_o)}{100} \right\} - 1 \right). \quad (2.6)$$

Before the start of the Industrial Revolution (about 1760), material consumption was small. Between then and now—an interval of 260 years—the cumulative production has become so large that it has had global impact both on land and in the oceans. How long will it be before this exponentially growing demand generates as much again? Eq. (2.6) can answer that. The result is that the doubling time for cumulative production is the same as that for annual production: $70/r$. This illustrates one of the more striking features of exponential growth: at a global growth rate of just 3% per year we will mine, process, and dispose of more “stuff” in the next 25 years than in the entire 250 years since the start of the Industrial Revolution.⁵ A sobering thought.

2.5 Summary and conclusions

Humanity’s use of materials is immense and growing. Our collective anthropogenic material flows are now a geological force, equaling in magnitude other natural geological phenomena. The energy required to make these materials, and the carbon emissions associated with this production, are also huge, consuming 15% of the total global primary energy use per year and a similarly large proportion of anthropogenic carbon emissions.

This chapter describes the orders of magnitude of the flow of materials, energy, and water that material production entails. The growth in demand over time is approximately exponential, meaning that consumption grows at a rate that is proportional to its current value—for most materials it is between 3% and 6% per year. Exponential growth has a number of consequences. One is that consumption doubles every $70/r$ years, where r is the growth rate in percent per year. It also means that the total amount consumed (the integral of the consumption over time) also doubles in the same time interval.

Behind all this is a bigger issue: the tight coupling between materials, energy, and carbon. Energy is needed to make materials. Materials are needed to make usable energy. Water is needed for both. Emissions are unavoidable if materials are made and energy is used. This chapter sets the scene for a fuller exploration of this coupling later in the book.

2.6 Further reading

BP (2018) Statistical Review of World Energy (2018) <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf> (*An annual review of world energy*. See also IRENA (2018)).

⁵The proof of this statement can be found in the solution to exercise E2.17, detailed in the Solution Manual for the exercises of this book.

- Gutowski, T.G., Sahni, S. Allwood, J.M. and Ashby, M.F. and Worrell, E. (2013) "The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand" *Phil. Trans. Roy. Soc. A* 371: 20120003. <http://rsta.royalsocietypublishing.org/content/371/1986/20120003>.
- Harvey, L.D.D. (2010) "Energy and the new reality 1: energy efficiency and the demand for energy services", Earthscan Ltd, London. ISBN 978-1-84971-072-5. (*An analysis of energy use in buildings, transport, industry, agriculture and services, backed up by comprehensive data.*)
- Herendeen R. A. (1998) "Ecological numeracy: quantitative analysis of environmental issues" John Wiley & Sons, NY. ISBN: 0471183091. (*Mathematical modeling of environmental trends and problems*).
- IRENA (2018) International Renewable Energy Agency <https://www.irena.org/publications/2017/Jul/Renewable-Energy-Statistics-2017> (*Statistics for capacity-power and energy delivered by renewable energy sources. See also BP (2018).*)
- Shell Petroleum (2007) "How the energy industry works", Silverstone Communications Ltd., Towchester, UK. ISBN 978-0-9555409-0-5. (*Useful background on energy sources and efficiency.*)
- Shiklomanov I.A. (2010) "World water resources and their use" UNESCO International Hydrological Programme, www.webworld.unesco.org accessed July 2010 (*A detailed analysis of world water consumption and emerging problems with supply.*)
- USGS Mineral Information (2018), "Mineral yearbook" and "Mineral commodity summary", <https://minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf> (*The gold-standard information source for global and regional material production, updated annually.*)
- Wolfe, J.A. (1984), "Mineral Resources—A World Review" Chapman & Hall, ISBN 0-4122-5190-6 (*A survey of the mineral wealth of the World, both for metals and non-metals, describing its extraction and the economic importance of each.*)

2.7 Exercises

E2.1. Ore grades. The average concentration of iridium in the earth's crust is $3 \times 10^{-10}\%$ by weight. The price of iridium is about \$14,000/kg. Use the approximate Eq. (2.1):

$$C_m \approx \frac{10}{G},$$

to estimate the grade G of the ore from which iridium is drawn. How does this compare with the average concentration in the earth's crust?

Global Ti production	
Year	Tonnes/year
1980	22,000
1985	19,000
1990	20,000
1995	31,000
2000	50,000
2005	78,000
2010	104,000
2015	110,000
2017	170,000

USGS Minerals Commodity Summaries (2018)

E2.2. Growth rate of titanium production. The table lists the production of titanium, in tonnes per year, over time. Plot the data onto a copy of the right-hand side of Fig. 2.11 of the text, plotting $\log(\text{production})$ against time. What, approximately, is the average growth rate of production of titanium between 1980 and 2017?

E2.3. Doubling times. The world consumption rate of CFRP is rising at 12% per year. How long does it take to double?

E2.4. Demand and supply for lithium. Most hybrid and electric vehicles (eVs) use lithium-ion batteries. An eV using today's technology requires, on average, about 8 kg of lithium. In 2017, eV production was 1.7 million, growing at 23% per year. In the same year, the global production of lithium was 43,000 tonnes. If lithium production remains unchanged, how long will it be before the demand for lithium for eVs exceeds current production?

E2.5. Growth rate of eV sales. Global sales of eVs in 2017 was 1.7 million units and is growing exponentially. Sales are expected to double by 2020. What is the expected growth rate?

E2.6. Rare-earth elements. Use the Internet to research rare-earth elements. What are they? Why are they important? Why is there concern about their availability?

E2.7. Rare-earth element production. The world production of rare-earth elements has risen from 60,000 tonnes in 1994 to 138,000 tonnes in 2018 and is growing exponentially. What is the growth rate? How long does it take for production to double?

E2.8. Growth rate of lithium production. “Lithium production, driven by electric vehicle production, is expected to rise by 23% over the next two years” (*Bloomberg Technology*, July 28, 2019). What is the growth rate of lithium production? What is the doubling time of production?

E2.9. Growth in gold mining. Global gold mine production, P_o , of gold in 2018 was 3332 tonnes, up 2% from the previous year. If this growth rate continues, what is the expected production in 2030?

E2.10. Demand and supply for platinum. The global production of platinum in 2017 was 224 tonnes, of which a quarter was derived from recycling (http://www.platinum.matthey.com/documents/new-item/pgm%20market%20reports/pgm_market_report_may_2017.pdf). That may not sound like much, but at the current price of US\$32/g it is worth about US\$6.9 billion (6.3×10^9). The catalytic converter of a car requires about 2 g of platinum-group metals, of which 75% is platinum. Car manufacture in 2017 was approximately 74 million vehicles. If all have catalytic converters, what fraction of the world production of platinum is absorbed by the auto industry?

E2.11. Water consumption. Global water consumption has tripled since 1970. What is the growth rate, $r\%$, in consumption C assuming exponential growth? By what factor will water consumption increase between now (2020) and 2050?

E2.12. Exponential growth: the parking problem. In 2008, there were 65 million cars on Chinese roads. By the end of 2018, this had increased to 240 million. If growth is exponential, what is the average growth rate of car numbers in China?

- (a) If this growth continues, how many cars will be on China’s roads in 2030?
- (b) Conduct a sanity check. What is the population of China today? How fast is it growing? Is the car population calculated in (a) really going to continue until 2030? Use the Internet to find the data you need.

E2.13. Mining the past. Hybrid and electric car production is currently (2018) growing at $r = 31\%$ per year worldwide. The cars have an average life of $\Delta t = 13$ years. The rare-earth metal *neodymium* is an ingredient of high-field permanent magnets at present used for their motors. If $f = 80\%$ of the neodymium in these motors can be recovered at end of life, what fraction of future neodymium demand for car motors can be met?

Electronic waste	kg/tonne
Plastics	300
Glass and ceramics	300
Copper	200
Iron	80
Tin	40
Silver	2
Gold	0.6
Palladium	0.1
Other	77.3

E2.14. Electronic waste (1). The world sale of smartphones in 2017 was 1.54 billion units. The average smartphone weights 150 g and has a composition corresponding to that for electronic waste listed in the table. How much gold is required for the 2017 production of smartphones?

E2.15. Electronic waste (2). The average smartphone has a life of 3 years. Smartphone sales are increasing at $r = 3.3\%$ per year.

- (a) The global smartphone sales in 2017 were $C_0 = 1.54$ billion. What are the anticipated sales C in 2020?
- (b) If 15% of the gold content of waste smartphones can be recovered, what fraction of the gold for the 2020 production can be met?

E2.16. Competing growth rates. The table lists the 2017 production of CFRP and of titanium in tonnes per year together with the growth rate of production in percent per year. How long will it be before the production of CFRP in tonnes per year exceeds that of titanium?

Material	Production 2017 (tonnes per year)	Growth rate (%/year)
CFRP	100,000	12
Titanium	170,000	6

E2.17. Cumulative stock over time. A total of 23 million cars were sold in China in 2017; in 2008, the sale was 6.6 million. What is the annual growth rate of car sales, expressed as percent per year?

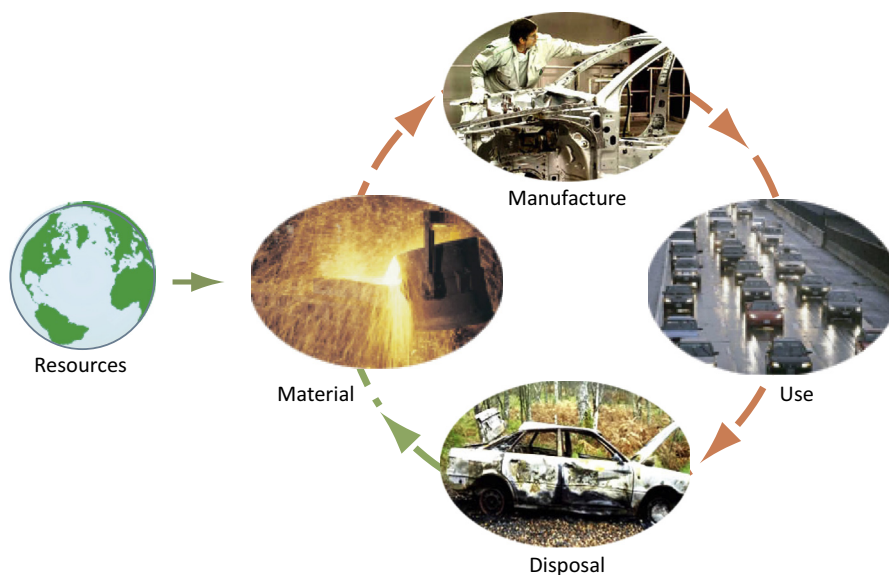
There were 210 million cars already on Chinese roads by the end of 2017. If this growth rate continues, how many cars will there be in 2030, assuming that half of those on the road today (2017) have been scrapped by then? Use Eq. (2.6) to find out.

E2.18. Production by weight and by volume. Tabulate the annual world production (tonnes/year) and the densities (kg/m^3) of carbon steel, PE, softwood, and concrete. You will find the data for these materials in Appendix A. Use an average of the ranges given in the data sheets. Calculate, for each, the annual world production measured in cubic meters/year. How does the ranking change?

Material	World production (tonnes/year)	Density (kg/m^3)
Iron	2.9×10^9	7850
Polyethylene	9×10^7	950
Softwood	2×10^9	620
Concrete	1.5×10^{10}	2450

E2.19. Doubling time for total material consumption. Prove the statement made in the text that, “at a global growth rate of just 3% per year we will mine, process, and dispose of more ‘stuff’ in the next 25 years than in the entire 250 years since the start of the Industrial Revolution.”

The materials life cycle



CONTENTS

- 3.1 Introduction and synopsis
- 3.2 The design process
- 3.3 The materials life cycle
- 3.4 Life-cycle assessment: details and difficulties
- 3.5 Streamlined life-cycle assessment
- 3.6 Eco-audits
- 3.7 Summary and conclusions
- 3.8 Further reading
- 3.9 Appendix: Software to support environmental life-cycle assessment
- 3.10 Exercises

3.1 Introduction and synopsis

The life cycle of a material has four phases. Materials are created from ores and feedstock. They are manufactured into products that are distributed and used. Products (like us) have a finite life, at the end of which they become scrap. The materials they contain, however, are still there; some (unlike us) can be resurrected and enter a second life as recycled content in a new product.

Life-cycle assessment (LCA) traces this progression, documenting the resources consumed and the emissions excreted during each phase of life. The output is a sort of biography, documenting where the materials have been, what they have done, and the consequences of this for their surroundings. It can take

Image of casting courtesy of SkillSpace; image of car production courtesy of US Department of Energy EERE program, image of cars courtesy of Reuters.com.

more than one form. A full LCA scrutinizes every aspect of life, an arduous and expensive task. Streamlined LCA and eco-audits provide a briefer character sketch, painting an approximate but still useful portrait of the materials' life.

Responsible design, today, aims to provide safe, affordable services while minimizing the drain on resources and the release of unwanted emissions. To do this, the designer needs an ongoing tally of the likely eco-impact of the design (or redesign) as it progresses. To be useful the tally must be fast, allowing quick "what if?" exploration of the consequences of alternative choices of material, use patterns, and end-of-life scenarios. A full LCA is not well adapted for this; it is too slow and expensive. *Streamlined LCA* and the *eco-audit methods* have evolved to fill the gap. They are approximate but still have sufficient resolution to guide decision-making.

This chapter is about the life cycle of materials and its assessment: how an LCA works, its precision (or lack of it), the difficulties of implementing it, and ways these difficulties can be bypassed to guide material choice in product design. The chapter starts with a brief introduction to the design process itself; we need that to see how the assessment and auditing methods mesh with design. It ends by introducing a strategy that is developed in the chapters that follow. There is an appendix describing currently available LCA and eco-audit software.

3.2 The design process

The starting point of a design is a *market need*; the end point is the full *specification* of a product that fills the need. It is essential to define the market need precisely, that is, to formulate a *need statement*, often in the following form: "a device is required to perform task X." Task X is expressed as a set of *design requirements*. Between the need statement and the product specification lie the stages shown in Fig. 3.1: the stages of *concept*, *embodiment*, and *detailed design*.

The design proceeds by developing concepts to perform the functions identified as design requirements. The next stage, embodiment, takes the promising concepts and seeks to analyze their operation at an approximate level. This involves sizing the components; identifying materials that will perform properly in the required ranges of stress, temperature, and chemical or thermal environment; and examining the implications for performance. The embodiment stage ends with a feasible layout, which is then passed to the detailed design stage. Here, specifications for each component are drawn up. Critical components are subjected to analysis to guarantee safety and life. Optimization methods resolve conflicts between competing objectives of minimizing cost and environmental burden while maximizing performance. A final choice of geometry and materials is made, and the methods of production are analyzed and costed out. The output of the detailed stage is a production specification from which a prototype can be constructed.

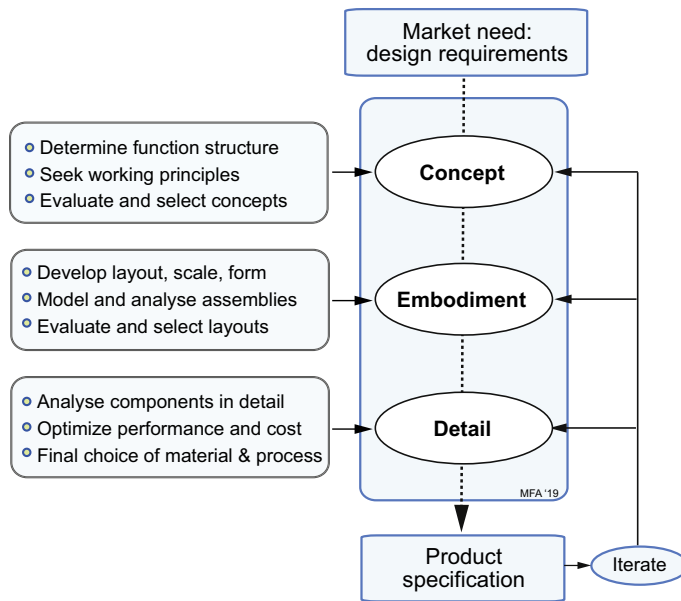


FIGURE 3.1 *The design process: requirements, concept, embodiment, detail, production.*

3.3 The materials life cycle

The idea of a *life cycle* has its roots in the biological sciences. Living organisms are born; they develop, mature, grow old, and, ultimately, die. The progression is built in—all organisms follow broadly the same path—but the way they develop, and their behavior, life span, and influence, depends on their interaction with their *environment*—the surroundings in which they live. Life sciences track the development of organisms and the ways in which they respond to their environment.

The life-cycle idea has been adapted and applied in other fields. In the social sciences it is the study of the interaction of individuals with their social environment. In the management of technology, it is the study of the birth, maturity, and decline of innovations in the commercial environment. Concern about resource depletion and the damaging effects of emissions focuses attention on yet another application of the idea: the life cycle of manufactured products and their interactions with the natural environment. Materials are central to these interactions.

Fig. 3.2 is a sketch of the materials life cycle. Ore, feedstock, and energy are drawn from the planet's natural resources and processed to give materials. These are manufactured into products that are distributed, sold, and used. Products have a useful life, at the end of which they become, in the eyes of the owner, waste.

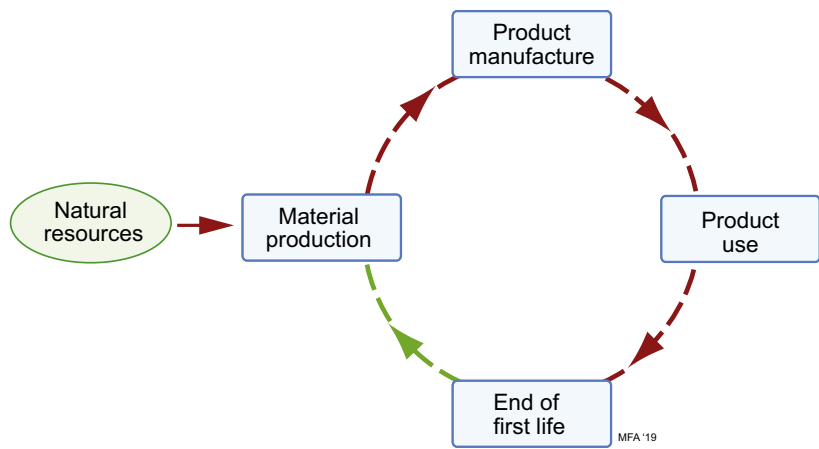


FIGURE 3.2 *The materials life cycle. Ore and feedstock are mined and processed to yield a material, manufactured into a product that is used, and, at the end of first life, discarded, recycled, reconditioned, or reused, as explored in Chapter 4.*

Energy and materials are consumed at each point in the life cycle, depleting natural resources (Fig. 3.3). There is an associated penalty of carbon dioxide, CO_2 ; oxides of sulfur, SO_x , and of nitrogen, NO_x , and other emissions in the forms of gaseous, liquid, and solid waste and low-grade heat. In low concentrations most

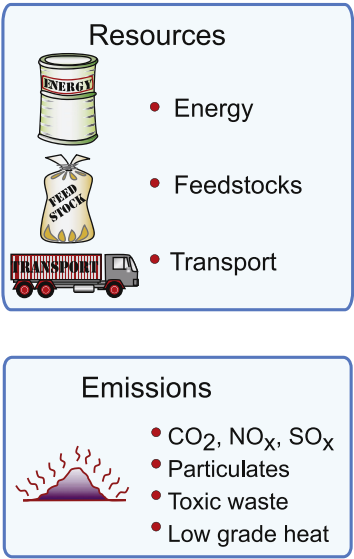


FIGURE 3.3 *Resources and emissions.*

of these are harmless, but as their concentrations build up they become damaging, creating an *environmental cost*. The problem, simply put, is that the sum of these unwanted by-products now often exceeds the capacity of the environment to absorb them. For some, the damage is local and the originator of the emissions accepts the responsibility and the cost of containing and fixing it (the environmental cost is said to be *internalized*). For others the damage is global and the creator of the emissions is not held directly responsible, so the environmental cost becomes a burden on society as a whole (it is *externalized*). The study of resource consumption, emissions, and their impacts is called *life-cycle assessment*.

Newsclip: China Wrestles with the Toxic Aftermath of Rare Earth Mining

Now, local and federal officials have shut down illegal and small-scale rare earth mining operations and embarked on a clean-up of polluted sites. "We hope that the environmental damage can stop and that these external [pollution costs] could be internalized in the cost" of products, Ma Jun, a leading Chinese environmentalist said.

Yale Environment 360, July 2, 2019

Newsclip: The world's most toxic town: the terrible legacy of Zambia's lead mines

Almost a century of lead mining and smelting has left a truly toxic legacy in the once-thriving town [Kabwe] in central Africa's Copperbelt.

The Guardian, May 28, 2017

3.4 Life-cycle assessment: details and difficulties

Formal methods for LCA first emerged in a series of meetings organized by the Society of Environmental Toxicology and Chemistry, of which the most significant were held in 1991 and 1993. This led, from 1997 on, to a set of standards for conducting an LCA, issued by the International Standards Organization (ISO 14040 and its subsections 14041, 14042, and 14043). These prescribe procedures for "defining goal and scope of the assessment, compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study." The study must (according to the ISO standards) examine energy and material flows in raw material acquisition, processing and manufacture, distribution, use, maintenance and repair, recycling options, and waste management.

There is a lot here and there is more to come. A summary in plainer English might help.

- *Goals and scope*: Why do the assessment? What is the product or service and which bits of its life are assessed?
- *Inventory compilation*: What resources are consumed? What emissions are released?
- *Impact assessment*: What do the resource consumption and emissions do to the environment—particularly, what bad things?
- *Interpretation*: What do the results mean? If bad, what can be done about it?

We look now at what each involves.

Goals and scope. Why do the study? Here are some possible answers:

- to guide the design of more environmentally friendly products;
- to demonstrate environmental awareness and responsibility;
- as an input to company sustainability reporting;
- to demonstrate eco-superiority relative to the competition;
- to be able to claim conformity to standards such as ISO 14040 and PAS 2050 (described later);
- because the enterprise to which you are a supplier or subcontractor requires it.

There is a wide spread of motives here; it would be surprising if one assessment method fitted the needs of them all.

And there is the question of scope: where should the LCA start and finish? Fig. 3.4 shows the four phases of life, each seen as a self-contained unit, with notional “gates” through which inputs pass and outputs emerge. If you were the manager of the manufacturing unit, as an example, your purpose might be to assess your plant, ignoring the other three phases of life because everything outside your gates is beyond your control. This is known as a “gate-to-gate” study, its scope limited to the activity inside the box labeled system boundary A. There is a tendency for the individual life phases to seek to minimize energy use, material waste, and internalized emission costs spontaneously, because it saves money to do so. But this action by one phase may have the result of raising resource consumption and emissions of the others. For example, if minimizing the manufacturing energy and material costs for a car results in a heavier vehicle and one harder to disassemble at its end of life, then the gains made in two phases have caused losses in two of the others. Put briefly: the individual life phases tend to be self-optimizing; the system as a whole does not. We return to this in later chapters in which trade-off methods are developed.

If the broader goal is to assess the resource consumption and emissions of the product over its entire life, the boundary must enclose all four phases (system boundary B). The scope becomes that of product birth to product death.

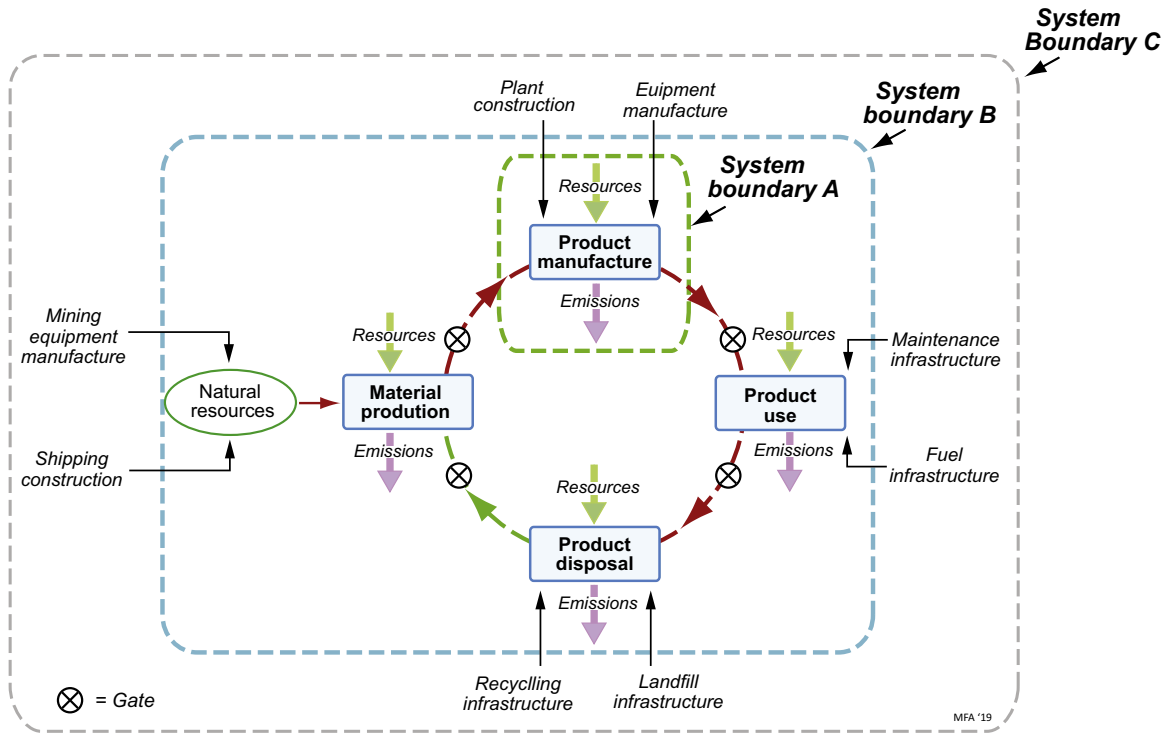


FIGURE 3.4 Life-cycle assessment system boundaries with the flows of resources and emissions across them. System boundary A encloses a single phase of the life cycle. System boundary B encloses the direct inputs and emissions of the entire life. It does not make sense to place the system boundary at C, which has no well-defined edge.

Some LCA proponents see a still more ambitious goal and grander scope (system boundary C). If ores and feedstock are included (as they are within system boundary B), why not the energy and material flows required to make the equipment used to mine them? And what about the resource and emission flows to make the equipment that made *them*? It is the “infinite recession” problem. Here an injection of common sense is needed. Setting the boundaries at infinity gets us nowhere. Equipment makers generally make equipment for other purposes too, and this gives a dilution effect: the more remote they are, the smaller is the fraction of their resources and emissions that can be assigned to the product being assessed. The standards are vague on how to deal with this point, merely instructing that the system boundary “shall be determined,” leaving the scope of the assessment to the judgment of the assessor. Input–output analysis gives a formal structure for dealing with these remoter contributions, but we shall leave that for later. For now, the practical way forward is to include only the primary flows directly required for the materials, manufacture, use, and disposal, excluding the secondary ones needed to make the primary ones possible.

Inventory compilation. Setting the boundaries is the first step. The second is data collection: amassing an inventory of the resource flows passing into the system and the emissions passing out. But how should these be measured? Per kilogram of final product? Yes, if the product is sold and used by weight. Per cubic meter of final product? Yes, if it is sold by volume. But few products are sold and used in this way. More usually it is neither of these, but *per unit of function*. The function of a container for a soft drink (a plastic water bottle or a Pepsi can) is to contain fluid. The bottle maker might measure resource flows per bottle, but if the idea is to compare containers of different size and material, then the logical measure is the resources consumed *per unit volume of fluid contained*. The function of a refrigerator is to provide a cooled environment. The maker might measure resource flows per fridge, but the logical measure from a life-cycle standpoint is the resource consumption *per unit of cooled volume per unit of time* (cold space/m³/year).

We will find that the functional units of resource entering one phase are not the same as those leaving it. There is nothing subtle about this, it's just to make accounting easier. Thus the flow of materials leaving phase 1 of life and entering phase 2 *are* traded by weight, so the functional unit here is "per unit weight": the embodied energy of copper, for instance, is listed as 59 MJ/kg. The output of phase 2 is a product; here "per product" might be used. In the use phase it is the function performed by the product that is of central importance and here the logical measure is "per unit of function."

The inventory analysis, then, assesses resource consumption and emissions per functional unit. The level of detail—the granularity—of the assessment is important. It doesn't make sense to include every nut, bolt, and rivet. But where should the cutoff come? One proposal is to include the components that make up 95% of the weight of the product, but a reservation is needed here. Electronics, for instance, don't weigh much, but the resources and emissions associated with their manufacture can be large, a point we return to in Chapter 6. Certain precious metals—platinum, rhodium, gold—are energy and carbon intensive. If exception is made for these, the 95% rule becomes practical.

Fig. 3.5 is a schematic of the start of an inventory analysis for a washing machine. Most of the parts are made of steel, copper, plastics, and rubber. Both materials production and product manufacture require carbon-based energy with associated emissions of CO₂, NO_x, SO_x, and low-grade heat. The use phase consumes water as well as energy, with contaminated water as an emission. Disposal of the washing machine creates burdens typical of any large appliance.

Impact assessment. The inventory, once assembled, lists resource consumption and emissions, but they are not all equally malignant; some are of more concern than others. Impact categories include *resource depletion*, *global warming potential*, *ozone depletion*, *acidification*, *eutrophication*¹, *human toxicity*,

¹The overenrichment of a body of water with nutrients—phosphates, nitrates—resulting in excessive growth of organisms and depletion of oxygen.

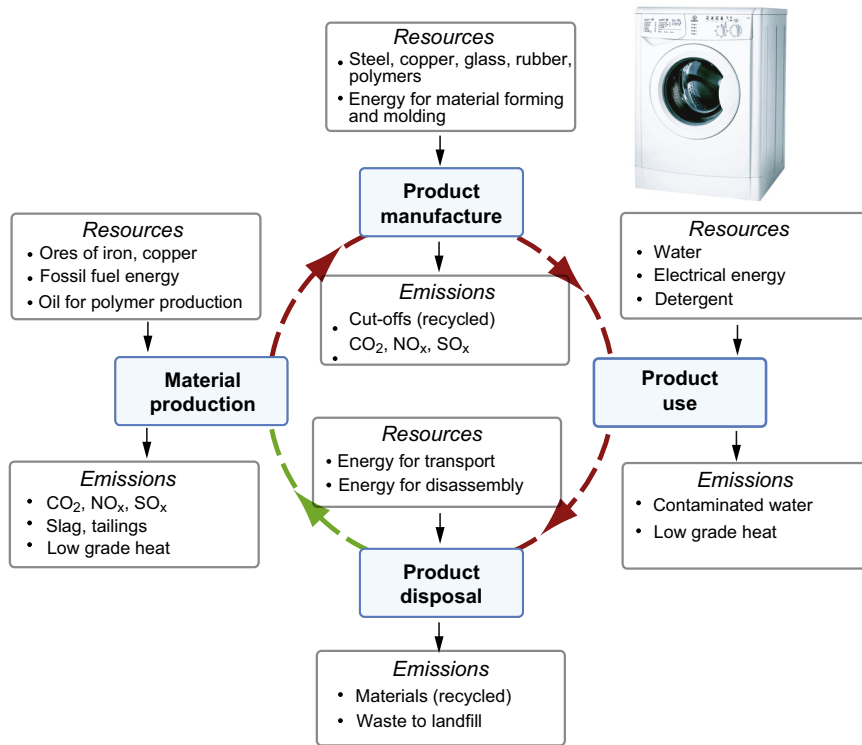


FIGURE 3.5 The principle resources and emissions associated with the life cycle of a washing machine.

and more. Each impact is calculated by multiplying the quantity of each inventory item by an *impact assessment factor*²—a measure of how profoundly a given inventory type contributes to an impact category. Table 3.1 lists examples of these for assessing global warming potential. The overall impact

Table 3.1 Global warming potential impact assessment factors

Gas	Impact assessment factor
Carbon dioxide, CO ₂	1
Carbon monoxide, CO	1.6
Methane, CH ₄	21
Dinitrous monoxide N ₂ O	256

²Normalization and impact assessment factors can be found in PAS 2050 (2008).

contribution to each category is found by multiplying the quantity of each emission by the appropriate impact assessment factor and summing the results.

Interpretation. What do these inventory and impact values mean? What response is appropriate? The ISO standard requires answers to these questions but gives little guidance about how to reach them beyond suggesting that it is a matter for specialists.

All this makes a full LCA a time-consuming matter requiring experts. Expert time is expensive. A full LCA is not something to embark on lightly. And while it is very detailed, it is not necessarily very precise.

The output and its precision. Fig. 3.6 is part of the output of an LCA—here, one for the production of aluminum cans (it stops at the exit gate of the manufacturing plant, so this is a “cradle-to-gate” not a “cradle-to-grave” study). The functional unit is “per 1000 cans.” There are three blocks of data. The first is an inventory of resources of ores, feedstock, and energy. The second is a catalog of emissions of gases and particulates. The third is an assessment of impacts—only some of them are shown here.

Despite the formalism that attaches to LCA methods, the results are subject to considerable uncertainty. *Resource* and *energy* inputs can be monitored in a straightforward and reasonably precise way. Measuring *emissions* is more difficult; few are known to better than $\pm 10\%$. Assessments of *impacts* depend on values for the impact assessment factors; here the uncertainties are much greater.

And there are two further issues, both troublesome. First, what is a designer supposed to do with these numbers? The designer, seeking to cope with the many interdependent decisions that any design involves, finds it hard to know how to use data like those of Fig. 3.6. How are energy or CO₂ and SO_x emissions to be balanced against resource depletion, energy consumption, global warming

Aluminum cans, per 1000 units		
Resource consumption	• Bauxite	59 kg
	• Oil fuels	148 MJ
	• Electricity	1572 MJ
	• Energy in feedstocks	512 MJ
	• Water use	1149 kg
Emissions inventory	• Emissions: CO ₂	211 kg
	• Emissions: CO	0.2 kg
	• Emissions: NO _x	1.1 kg
	• Emissions: SO _x	1.8 kg
	• Particulates	2.47 kg
Impact assessment	• Ozone depletion potential	0.2 x 10 ⁹
	• Global warming potential	1.1 x 10 ⁹
	• Acidification potential	0.8 x 10 ⁹
	• Human toxicity potential	0.3 x 10 ⁹

FIGURE 3.6 Typical life-cycle assessment output showing three categories: resource consumption, emission inventory, and impact assessment.

potential, or human toxicity? They are not measured in the same units and they differ, in the example of Fig. 3.6, by 10 orders of magnitude. And second, how is the assessment to be paid for? A full LCA involves experts and takes days or weeks. Performing multiple LCAs as a design evolves is impractical. LCA has value as a *product assessment tool*, but it is not a *design tool*.

Aggregated measures: eco-indicators. The first of these difficulties has led to efforts to condense the LCA output into a single measure called an *eco-indicator*. To do this, four steps are necessary, shown in Fig. 3.7. The first is that of *classification* of the data listed in Fig. 3.6 according to the impact caused by each (global warming, ozone depletion, acidification, etc.). The second step is that of *normalization* to remove the units and reduce the data to a common scale (0–100, for instance). The third step is that of *weighting* to reflect the perceived seriousness of each impact. Global warming might be seen as more serious than resource depletion, giving it a larger weight. In the final step, the weighted, normalized measures are *summed* to give the indicator.³

The use of eco-indicators is criticized by some. The grounds for criticism are that there is no agreement on normalization or weighting factors, that the method is opaque since the indicator value has no simple physical significance, and that defending design decisions based on a measurable quantity like *energy consumption* or *carbon release to atmosphere* carries more conviction than doing so with an indicator.

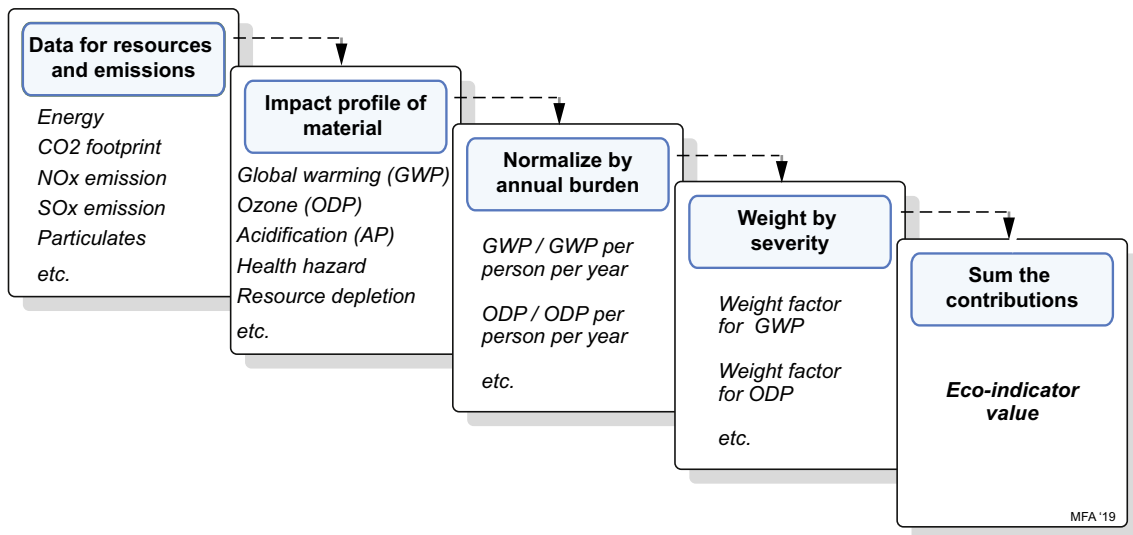


FIGURE 3.7 The steps in calculating an eco-indicator. Difficulties arise in steps 3 and 4: there is no agreement on how to choose the weight factors.

³Details can be found in EPS (1993), Idemat (1997), EDIP (1998), and Wenzel et al. (1997).

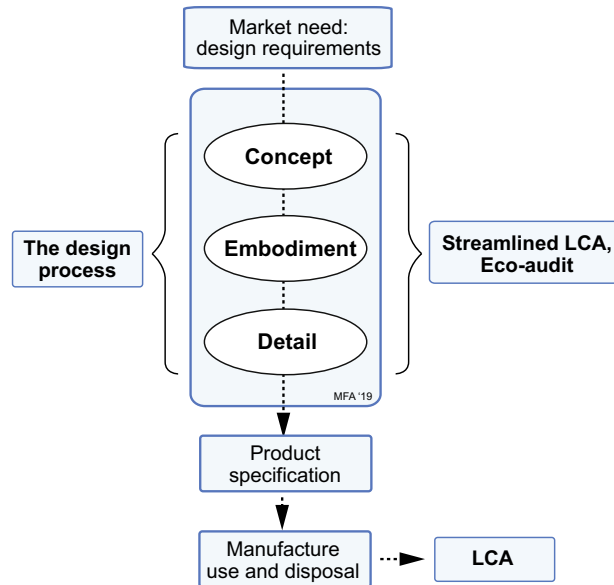


FIGURE 3.8 A life-cycle assessment (LCA) is an end-of-life assessment tool. Streamlined LCA and eco-audits are design tools.

In summary, an LCA offers the most complete and exhaustive analysis of the environmental impact of products. Software packages are available to ease the task—they are documented in the appendix to this chapter. But a full LCA remains slow, expensive, and data intensive, and much of the data is unavailable until the product has been manufactured and is in service. To guide design decisions, particularly the choice of materials, we need tools of a different sort, ideally with the ability to explore rapid “what if?” scenarios, allowing the designer to scan alternative options quickly (Fig. 3.8). That’s where streamlined methods can help.

3.5 Streamlined life-cycle assessment

Emerging legislation imposes ever-increasing demands on manufacturers for eco-accountability. The EU Directive 2005/32/EC on energy-using products (EuPs), for example, requires that manufacturers of EuPs must demonstrate “that they have considered the use of energy in their products as it relates to materials, manufacture, packaging, transport, use and end of life.” This sounds horribly like a requirement for a full LCA for each one of their products. Many manufacturers make hundreds of different products. The expense both in money and time would be prohibitive.

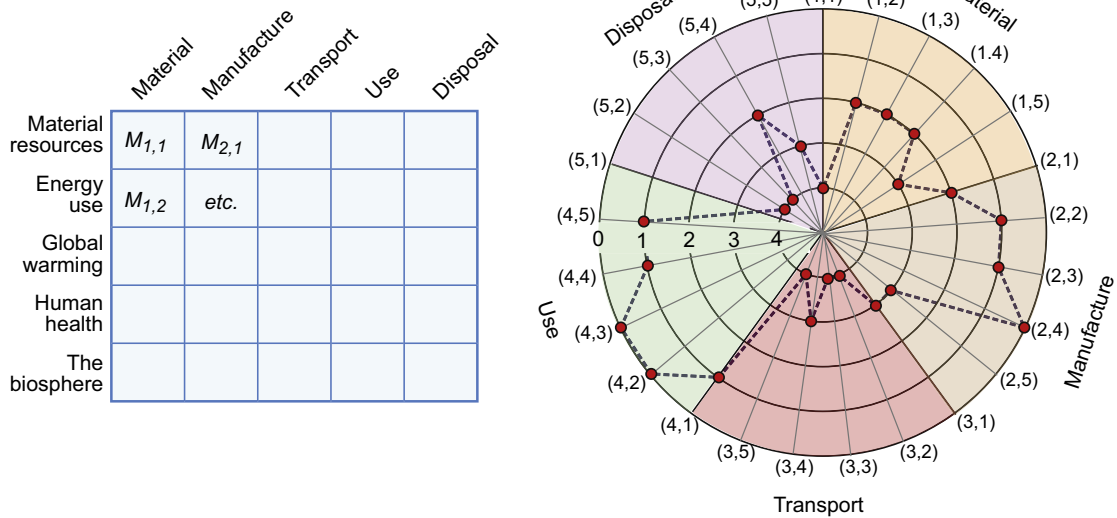


FIGURE 3.9 An example of a streamlined life-cycle assessment matrix (left) and a target plot (right) displaying the rankings in each element of the matrix. In this example the use phase gets poor ratings.

The matrix method. The *streamlined LCA*⁴ attempts to overcome this by using a reduced inventory of resources and accepting a degree of approximation. The matrix on the left of Fig. 3.9 shows the idea. The life phases appear as the column headers, the impacts as the row headers. An integer between 0 (highest impact) and 4 (least impact) is assigned to each matrix element M_{ij} , based on experience guided by checklists, surveys, or protocols.⁵ The overall *environmentally responsible product rating*, R_{erp} , is the sum of the matrix elements:

$$R_{erp} = \sum_i \sum_j M_{ij} \quad (3.1)$$

Alternative designs are ranked by this rating.

The information in the matrix is displayed in a more visual way as a target plot, shown on the right of Fig. 3.9. It has five concentric circles corresponding to the ranking 0 (highest impact) to 4 (least impact); the elements of the matrix are plotted as dots on radial lines, one line for each element of the matrix. For an “ideal” product all the dots lie on the innermost ring, scoring a “bulls-eye.” A product with its dots near the outermost circle has much room for improvement.

⁴Graedel (1998); Todd and Curran (1999); see “Further reading” at the end of the chapter.

⁵Graedel (1998) provides an extensive protocol.

Example: an eco-comparison of 1950 and 1990s car⁶

The task. Table 3.2 is a low-resolution bill of materials and fuel consumption for typical cars of the 1950s and the 1990s. The 1950s car is heavier; made of relatively few materials, none of them of recycled origin; has poor fuel efficiency; and was dumped at end of life. The more modern car is lighter; made of a more complex mix of materials, some derived from recycling; has better fuel efficiency; and will be 80% recycled at end of life. Compare the eco-profiles of the two vehicles.

Answer. The “function” is powered family transport. The functional unit is one family-sized vehicle. The assessor chooses *energy efficiency*, *carbon efficiency*, and *material efficiency* as assessment criteria; “efficient” means that the function is provided with the minimum material use, energy use, and carbon emission. Using this background and considerable experience, the assessor assigns rankings of 0–4 to each element of the matrices shown in Fig. 3.10. The 1950s car scores an R_{erp} value of 18. The 1990s car scores 39. The corresponding target plots indicate that the eco-character of the 1990s car is rather better than that of the 1950s, particularly

Table 3.2 Material content of automobiles^a

Material	1950 car (kg)	1990 car (kg)
Iron	220	207
Steel	1290	793
Aluminum	0	68
Copper	25	22
Lead	23	15
Zinc	25	10
Plastics	0	101
Rubber	85	61
Glass	54	38
Platinum	0	0.001
Fluids	96	81
Other	83	38
Total weight	1901	1434
Fuel consumption	15 mpg	27 mpg

^aFrom Graedel (1998).

in its use and disposal phases. All very instructive, but how did the assessor arrive at the rankings? The answer is buried in the assessor's mine of accumulated experience. Do the absolute values of the numbers have significance? Clearly not. The energy used to propel a car over its life greatly exceeds that required to manufacture it in the first place. The matrix and target plot capture the issues, but not their relative importance. For that, we need numbers.

⁶ Data and basic methods from Graedel [1998].

There are many variants of the matrix approach, differing in the impact categories of the rows and the life (or other) categories of the columns. The method has the merits that it is flexible, is easily adapted to a variety of products, carries a low overhead in time and effort, and—in the hands of practitioners of great experience—can take the subtleties of emissions and their impacts into account. It has the drawback that it relies heavily on experience and judgment. It is not a tool to put in the hands of a novice. Is there an alternative?

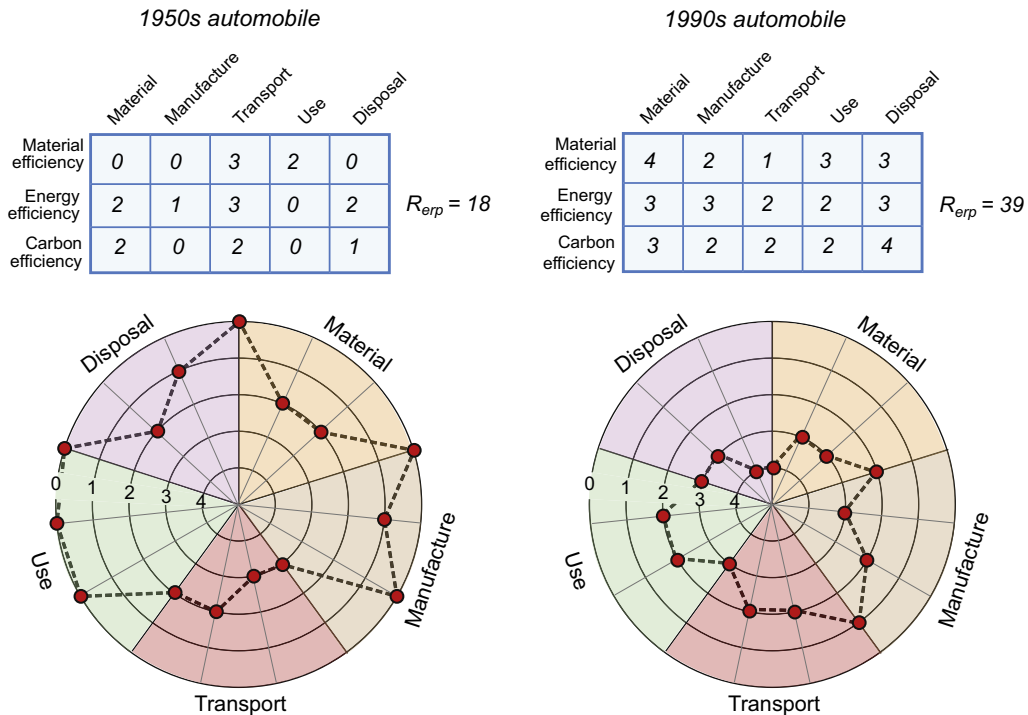


FIGURE 3.10 The assessment matrices and target plots for cars of the 1950s and the 1990s. The more modern car has a higher value of R_{erp} and a smaller enclosed area on the target plot.

3.6 Eco-audits

There is as yet no consensus on a single metric for the eco-impact of product life that is both workable and able to guide design. On one point, however, there is a degree of international agreement⁷: a commitment to a progressive reduction in carbon emissions, generally interpreted as meaning carbon (CO_2) or carbon equivalent ($\text{CO}_{2,\text{eq}}$), a value corrected for the global warming potential of the other gaseous emissions. At the national level the focus is more on reducing energy consumption, but since this and CO_2 production are closely related, reducing one generally reduces the other. Thus there is a certain logic in basing design decisions on one resource—energy—and one emission— CO_2 . They carry more conviction than the use of a more obscure indicator, as evidenced by the now-standard reporting of both energy efficiency and CO_2 emissions of cars and appliances (Fig. 3.11).

The point is that, of the many emissions associated with industrial activity, it is CO_2 that is of greatest current concern. It is global in its impact, causing harm to both the nations that generate a great deal of it and those that do not. It is closely related to the consumption of fossil fuels, themselves a diminishing resource and one that is a source of international tension. The IPCC reports described in Chapter 1 argue that cutting carbon emissions is a matter of urgency. At this stage in structuring our thinking about materials and the environment, taking energy consumption and the release of atmospheric CO_2 (or $\text{CO}_{2,\text{eq}}$) as metrics is a logical simplification.



FIGURE 3.11 It is now standard practice to report fuel economy and emissions figures for cars (e.g., combined, 42–46 mpg [5.9–6.4 L/100 km]; CO_2 emissions, 143–154 g/km) and energy ratings for appliances (e.g., 330 kWh/year, efficiency rating A).

⁷The Kyoto Protocol of 1997 and subsequent treaties and protocols, detailed in Chapter 5.

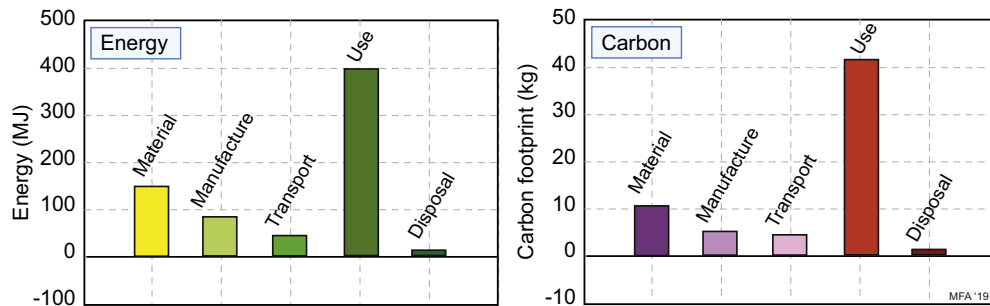


FIGURE 3.12 Breakdown of energy and carbon for each life phase.

Fig. 3.12 suggests the breakdown, assigning a fraction of the total life-energy demands of a product to material creation, product manufacture, transport, product use, and disposal. Product disposal can take many forms, some carrying an energy penalty, some allowing material recycling or energy recovery (Chapter 4).

When this distinction is made, it is frequently found that one of phases of life dominates the picture, as the use phase does in Fig. 3.12. Two conclusions follow. The first is that when one phase of life dominates, it is this phase that becomes the first target for redesign, since it is here that a given fractional reduction makes the biggest contribution. The second is that when differences are as great as those of Fig. 3.12, great precision is not essential because it is the ranking that matters. Modest changes to the input data leave the ranking unchanged. It is the nature of people who measure things to wish to do so with precision, and precision must be the ultimate goal. But it is possible to move forward without it: precise judgments can be drawn from imprecise data.

3.7 Summary and conclusions

Products, like organisms, have a life, during which they interact with their environment. Their environment is also ours; if the interaction is a damaging one, it diminishes the quality of life of all who share it.

LCA is the study and analysis of this interaction, quantifying the resources consumed and the wastes emitted. It is holistic, spanning the entire life, from the creation of the materials through the manufacture of the product, its use, and its subsequent disposal. Standards (the ISO 14040 series) prescribe procedures for conducting an LCA. Implementing them needs skill and requires access to much detail, making a full LCA expensive in both money and time, and one that delivers outputs that are not well adapted to the needs of designers.

This is no surprise. The technique of LCA is relatively new and is still evolving. The way forward is to adopt a less rigorous but much simpler approach, streamlining the assessment by restricting it to the key eco-aspects of most immediate concern. The matrix method, of which there are many variants, assigns a ranking

for each impact category in each phase of life, summing the rankings to get an environmentally responsible product rating. Another approach, better adapted to guiding material choice, is to limit the impact categories to one resource—energy—and one emission—CO₂—auditing designs as they evolve. Provided the resolution of the audit is sufficient to draw meaningful conclusions, the results can guide design decision-making without imposing an unacceptable burden of analysis. We return to eco-audits in Chapters 7 and 8.

3.8 Further reading

- Allwood, J.M. and Cullen, J.M. (2012) “Sustainable materials with both eyes open” UIT Press, Cambridge, UK. ISBN 978-1-906860-05-9. (*An analysis the impacts materials have on the environment.*)
- EU Directive on Energy Using Products (2005). Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council. (*One of several EU Directives relating to the role of materials in product design.*)
- GaBi (2008), PE International, Hauptstraße 111–113, 70771 Leinfelden-Echterdingen, Germany <http://www.gabi-software.com/>. (*GaBi is a software tool for product assessment to comply with European legislation.*)
- Goedkoop, M., Effting, S., and Collignon, M., (2000) “The Eco-indicator 99: A damage oriented method for Life-cycle Impact Assessment, Manual for Designers” (April 14, 2000) (<http://www.pre.nl>). (*An introduction to eco-indicators, a technique for rolling all the damaging aspects of material production into a single number.*)
- Graedel, T.E. (1998) “Streamlined Life-cycle Assessment”, Prentice Hall, NJ. (*Graedel is the father of streamlined LCA methods. The first half of this book introduces LCA methods and their difficulties. The second half develops his streamlined method with case studies and exercises. The appendix details protocols for informing assessment decision matrices.*)
- Graedel T.E. and Allenby, B.R. (2003) “Industrial ecology” 2nd edition, Prentice Hall, NJ. (*An established treatise on industrial ecology.*)
- Greene, J.P. (2014) “Sustainable Plastics – Environmental assessments of bio-based, biodegradable and recycled plastics”, Wiley, NJ. (*The sustainability aspects of both bio-based and petroleum-based plastics with particular emphasis on end-of-life.*)
- GREET (2015) Argonne National Laboratory and the US Department of Transport (<https://greet.es.anl.gov/greet.models>). (*Software for analyzing vehicle energy use and emissions.*)

- Guidice, F. La Rosa, G. and Risitano, A. (2006), "Product design for the environment" CRC/Taylor and Francis, London, UK. (*A well-balanced review of current thinking on eco-design.*)
- Heijungs, R. (editor) (1992) "Environmental life-cycle assessment of products: background and guide", Netherlands Agency for Energy and Environment.
- Idemat Software version 1.0.1 (2019), (<http://idematapp.com/>) Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands. (*An LCA tool developed by the University of Delft, Holland.*)
- ISO 14040 (1998) Environmental management – Life-cycle assessment – Principles and framework.
- ISO 14041 (1998) Goal and scope definition and inventory analysis.
- ISO 14042 (2000) Life-cycle impact assessment.
- ISO 14043 (2000) Life-cycle interpretation, International Organization for Standardization, Geneva, Switzerland. (*The set of standards defining procedures for life-cycle assessment and its interpretation.*)
- Kyoto Protocol (1997) United Nations, Framework convention on climate change. Document FCCC/CP1997/7/ADD.1 (*An international treaty to reduce the emissions of gases that, through the greenhouse effect, cause climate change.*)
- MacKay, D.J.C. (2008) "Sustainable energy – without the hot air", UIT Press, Cambridge, UK and www.withouthotair.com/. (*MacKay brings a welcome dose of common sense into the discussion of energy sources and use. Fresh air replacing hot air.*)
- MEEUP Methodology Report, final (2005), VHK, Delft, Netherlands (www.pre.nl/EUP/). (*A report by the Dutch consultancy VHK commissioned by the European Union, detailing their implementation of an LCA tool designed to meet the EU Energy-using Products directive.*)
- National Academy of Engineering and National Academy of Sciences (1997), "The industrial green game: implications for environmental design and management" National Academy Press, Washington DC, USA. ISBN 978-0309-0529-48. (*A monograph describing best practices that are being used by a variety of industries in several countries to integrate environmental considerations in decision-making.*)
- PAS 2050 (2008) "Specification for the assignment of the life-cycle greenhouse gas emissions of goods and services", ICS code 13.020.40, British Standards Institution, London, UK. ISBN 978-0-580-50978-0. (*A proposed European Publicly Available Specification (PAS) for assessing the carbon footprint of products.*)
- SETAC (1991) "A technical framework for life-cycle assessment," Fava, J.A., Denison, R. Jones, B. Curran, M.A. Vignon, B. Selke, S. and Barnum, J., (Eds) Society of environmental toxicology and chemistry, Washington, DC. (*The meeting at which the term Life-cycle Assessment was first coined.*)

- SETAC (1993) "Guidelines for life-cycle assessment – a code of practice," editor Consoli, F., Fava J.A., Denison, R. Dickson, K. Kohin, T. and Vigon, B. (Eds) Society of environmental toxicology and chemistry, Washington, DC. (*The first formal definition of procedures for conducting an LCA.*)
- Todd, J.A. and Curran, M.A. (1999) "Streamlined life-cycle assessment: a final report from the SETAC North America streamlined LCA workshop", Society of Environmental Toxicology and Chemistry, Washington, DC. (*One of the early moves towards streamlined LCA.*)
- Vezzoli, C. (2018) "Design for Environmental Sustainability", 2nd edition, Springer Verlag, London.

3.9 Appendix: Software to support environmental life-cycle assessment

The most common uses of LCA are for product improvement ("How can I make my products greener?"), support of strategic choices ("Is this or that the greener development path?"), benchmarking ("How do our products compare ...?"), and communication ("Our products are the greenest"). Most of the software tools designed to help with this use ISO 14040 to 14043 as the starting point. In doing so they commit themselves to a process of considerable complexity.⁸ There is no compulsion to follow this route, and some practitioners do not. Some of these are aimed at specific product sectors (vehicle design, building materials, papermaking). Others are aimed at the early stages of product design, and these, of necessity, are simpler in their structure. Two, at least, have education as a target. So there is quite a spectrum of software tools, eight of which are listed in Table 3.3 and reviewed next. Some of these tools are free, some can be bought, and others are available only through the services of a consultant; an understandable precaution, given their complexity.

SimaPro (2018). SimaPro, developed by PRé Consultants, is a widely used tool to collect, analyze, and monitor the environmental performance of products and services following the ISO 14040 series recommendations. There is an educational version. A free demo is available from the PRé website.

TEAM 5 (2018). TEAM 5 is Ecobilans LCA software. It allows the user to build and use a large database and to model systems associated with products and processes following the ISO 14040 series of standards.

GaBi (2018). GaBi Envision 3.0, developed by PE International, is a tool for product assessment to comply with European legislation. It has facilities for analyzing cost, environment, social and technical criteria, and optimization of processes. A demo is available.

REET (2018). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (REET) is a free spreadsheet running in Microsoft Excel

⁸PRé Consultants estimate that the time needed to perform a "screening" LCA is about 8 days, that for a full LCA is about 22 days.

Table 3.3 Life-cycle assessments and related software

Tool name	Provider
SimaPro	PRé Consultants (http://www.pre.nl)
TEAM 5 (Ecobilan)	PricewaterhouseCoopers (https://ecobilan.pwc.fr/en/team/team-demo.html)
GaBi Envision 3.0	PE International (http://www.gabi-software.com/uk-ireland/software/)
REET	US Department of Transport (http://www.transportation.anl.gov/)
MIPS	Wuppertal Institute (http://www.wupperinst.org/)
CES EduPack 2019	Granta Design, Cambridge, UK (www.grantadesign.com/education)
EIO-LCA	Carnegie Mellon Green Design Institute, USA (http://www.eiolca.net/)
LCA Calculator	IDC, London, UK(www.lcacalculator.com/)

developed by Argonne National Laboratory for the US Department of Transport. There are two versions, one for fuel-cycle analysis and one for vehicle-cycle analysis. They deal with specific emissions, not with impacts and weighted combinations. For a given vehicle and fuel system, the model calculates energy consumption, emissions of CO₂-equivalent greenhouse gases—primarily carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O)—and six criteria pollutants: volatile organic compounds, carbon monoxide (CO), nitrogen oxide (NO_x), particulate matter with size smaller than 10 µm, particulate matter with size smaller than 2.5 µm, and sulfur oxides (SO_x).

MIPS (2018). MIPS stands for material input per service unit, a metric for the environmental impacts caused by a product or service over its life. It enables material intensity analysis at both the micro-level (focusing on specific products and services) and the macro-level (focusing on national economies).

CES EduPack (2019). Granta Design specializes in materials information-management software. One of their products, CES EduPack, is a widely used materials-selection tool. It includes an eco-audit module.

EIO-LCA (2018). The economic input–output LCA (EIO-LCA) of Carnegie Mellon University calculates sector emissions based on input–output data for the sectors of the North American Industry Classification System. It is not designed for the assessment of products. A demo is available.

LCA Calculator (2018). This is a quick and intuitive way for designers and engineers to understand, analyze, and compare environmental impacts of products and particular design decisions.

3.10 Exercises

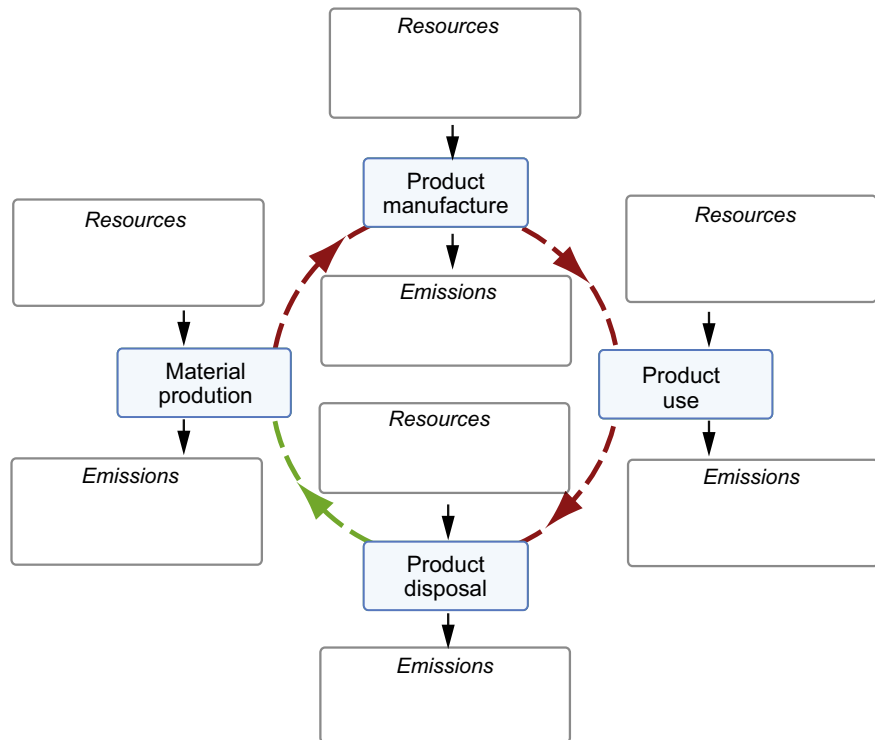
E3.1. Resources and emissions (1).

(a) Which phase of life would you expect to be the most energy intensive (in the sense of consuming fossil fuel) for the following products?

- a plastic bucket
- a toaster
- a 2018 Toyota Land Cruiser Wagon 4WD
- a bicycle
- a motorbike
- a refrigerator
- a coffee maker
- a liquefied petroleum gas-fired patio heater

E3.2. Resources and emissions (2).

Pick one of the products listed in Exercise E3.1 and itemize the resources and emissions associated with each phase of its life along the lines of Fig. 3.5 of the text.



The Figure above is a template for listing the principle resources and emissions associated with the life of a product.

- E3.3. Functional units.** Think of the basic need filled by the products listed below. List what you would choose as the functional unit for an LCA.

Product

Washing machines
Refrigerators
Home heating systems
Air conditioners
Lighting
Home coffee maker
Public transport
Hand-held hair dryers

- E3.4. Environmental cost.**

- (a) What is meant by “externalized” costs and costs that are “internalized” in an environmental context?
- (b) Now, a moment of introspection. List three externalized costs associated with your life style. If your life is so pure that you have fewer than three, then list some of other people you know.

- E3.5. System boundaries.** What, in the context of LCA, is meant by “system boundaries”? How are they set?

- E3.6. The LCA process.** Describe briefly the steps prescribed by the ISO 14040 standard for LCA of products.

- E3.7. Limitations of LCA.** What are the difficulties with a full LCA? Why can a simpler, if approximate, technique be helpful?

- E3.8. Streamlined LCA.** Pick one of the products listed in Exercise E3.1 and, using your judgment, attempt to fill out the following simplified streamlined LCA matrix to give an environmentally responsible product rating, R_{erp} . Make your own assumptions (and report them) about where the product was made, and thus how far it has to be transported, and whether it will be recycled. Assign an integer from 0 (lowest impact) to 4 (highest impact) to each box and then sum them up to give an environmental rating, providing a comparison. Try the following protocol:

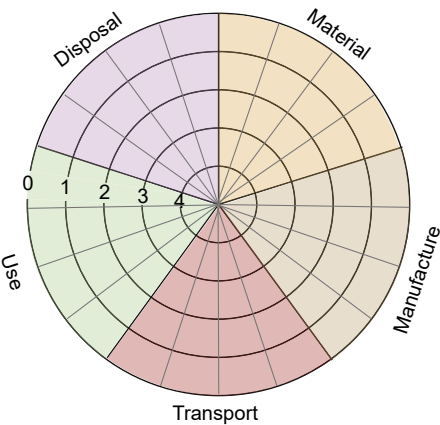
- **Material:** Is it energy intensive? Does its production create damaging emissions? Is it difficult or impossible to recycle? Is it

toxic? If the answer to all these questions is *yes*, score 4. If the reverse, score 0. Use the intermediate integers for other combinations.

- **Manufacture:** Is the process one that uses much energy? Is it wasteful (meaning cutoffs and rejects are high)? Does it produce toxic or hazardous waste? Does it make use of volatile organic solvents? If yes to all, score 4. If no, score 0, etc.
- **Transport:** Is the product manufactured far from its ultimate market? Is it shipped by air freight? If yes to both, score 4. If no to both, score 0.
- **Use:** Does the product use energy during its life? Is the energy derived from fossil fuels? Are any emissions toxic? Is it possible to provide the use—function in a less energy-intensive way? Score as before.
- **Disposal:** Will the product be sent to landfill at its end of life? Does disposal involve toxic or long-lived residues? Score as before.

What difficulties did you have? Do you feel confident that the results are meaningful?

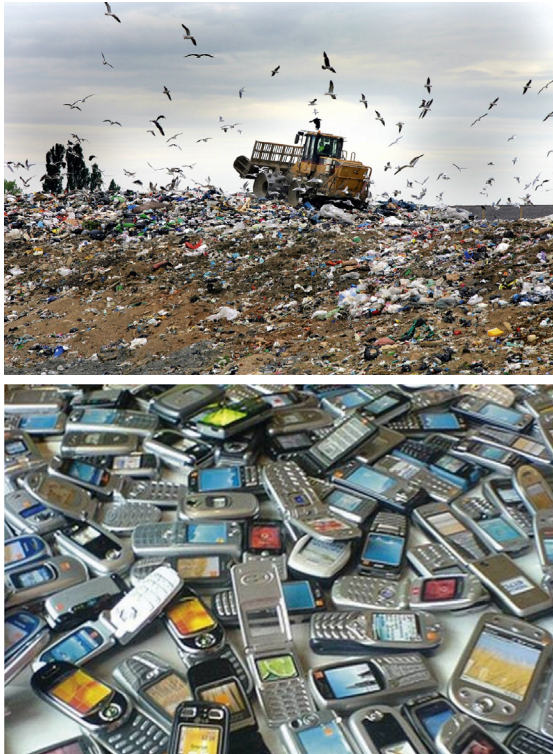
	Material	Manufacture	Transport	Use	Disposal
Material resources (high use = 0, none = 4)					
Energy use (high use = 0, none = 4)					
Global warming (much CO ₂ = 0, no CO ₂ = 4)					
Human health (Toxic emissions or waste?)					
Column totals					
<i>Rerp</i> = Sum across column totals					



End of first life: a problem or a resource?

CONTENTS

- 4.1 Introduction and synopsis
- 4.2 What determines product life?
- 4.3 End-of-first-life options
- 4.4 The problem of packaging
- 4.5 Recycling: resurrecting materials
- 4.6 Summary and conclusions
- 4.7 Further reading
- 4.8 Appendix: Designations used in recycle marks
- 4.9 Exercises



4.1 Introduction and synopsis

When stuff is useful, we show it respect and call it “material.” When the same stuff stops being useful, we cease to respect it and call it “waste.” Waste is deplorable,

Is this waste or is it a resource? Image courtesy Envirowise—Sustainable Practices, Sustainable Profits, a UK government program managed by Wrap.org.uk. Image of phones courtesy Recycling bins.uk <https://www.recyclingbins.co.uk/about/>.

and it is much deplored, that from packaging particularly so. Is it inevitable? The short answer is *yes*—it is a consequence of one of the inescapable laws of physics: entropy can only increase. A fuller answer is *yes, but*. The “but” has a number of aspects. That is what this chapter is about.

First, a calibration. We (the global we) are consuming materials at an ever-faster rate (Chapter 2). The first owner of a product, at the end of its first life, rejects it as “waste.” So waste, too, is generated at an ever-growing rate. What happens to it? In five words: *landfill, combustion, recycling, reengineering, or reuse*. That sounds comprehensive—it must be feasible to find a home for cast-off products in one of these. Ah, but. To be effective, the capacity of a channel for absorbing products at the end of first life must match the rate of rejection. Only one of the five has any real hope of achieving this. And then there are the economics: a business case exists only if someone, somehow, profits from it. End of life is not simple.

Value is added when ores and feeds are processed into materials and these are used to make products. How much of this value can be retained or recovered? Energy is added, too. The energy invested in mining a resource and transforming it into a material is known as the “embodied energy” of the material (units: MJ/kg). How much of the embodied energy can be salvaged at end of life? This is a question we explore here and return to in Chapter 13 with the vision of a circular materials economy.

But now, back down to earth. To start at the beginning: why do we throw things away?

4.2 What determines product life?

The rapid turnover of products we see today is a comparatively recent phenomenon. In earlier times, furniture was bought with the idea that it would fill the needs of not just one generation but several—treatment that, today, is reserved for works of art. A wristwatch, a gold pen, were things you used for a lifetime and then passed on to your children. No more. Behind all this is the question of whether the *value* of a product increases or decreases with age.

A product reaches the end of its life when it is no longer valued. The cause of the demise is, frequently, not the obvious one that the product just stopped working. The life expectancy is the shortest of:¹

- the *physical life*, meaning the time in which the product breaks down beyond economic repair;
- the *functional life*, meaning the time when the need for it ceases to exist;
- the *technical life*, meaning the time at which advances in technology have made the product unacceptably obsolete;

¹This list is a slightly extended version of one presented by Woodward, DG (1997), in “Life-cycle costing,” *Int. J. Project Management*, Vol. 15, pp. 335–344.

- the *economical life*, meaning the time at which advances in design and technology offer the same functionality at significantly lower operating cost;
- the *legal life*, the time at which new standards, directives, legislation, or restrictions make the use of the product illegal;
- and finally, the *desirability life*, the time at which changes in taste, fashion, or aesthetic preference render the product unattractive.

One obvious way to reduce resource consumption is to extend product life by making the product more durable. But durability has more than one meaning: we have just listed six. Materials play a role in them all—something that we return to later. Accept, for the moment, that a product *has*, for one reason or another, reached the end of its first life. What are the options?

4.3 End-of-first-life options

Fig. 4.1 introduces the choices: *landfill*, *combustion for heat recovery*, *recycling*, *reengineering*, and *reuse*.

Landfill. Much of what we now reject is committed to landfill. Already there is a problem: the land available to “fill” in this way is already, in some European countries, almost full. Recall one of the results of Chapter 2: if the consumption of materials grows by 3% per year we will use and discard as much stuff in the next 25 years as in the entire history of industrialization. Most European nations today impose a landfill tax, currently (in 2019) ranging from €40 to €90 per tonne and rising, seeking to divert waste into the other channels of Fig. 4.1. These must be capable of absorbing the increase. None, at present, can.

Combustion with energy recovery. Materials, we know, contain energy. Rather than throwing them away, it would seem better to recover some of this energy by controlled combustion. Not as easy as it sounds. First, the combustibles must be separated (Fig. 4.2). The combustion must be carried out under controlled conditions that do not generate toxic fumes or residues, requiring high temperatures, sophisticated control, and expensive equipment. The energy recovery is imperfect partly because it is incomplete and partly because the incoming waste carries a moisture content that has to be boiled off. The efficiency of thermal energy recovery from the combustion process is at best 50%. If the recovered heat is used to generate electricity, it falls to 15%. The carbon consequences are bad: all the carbon that the combustible materials contain is emitted as CO₂. And communities don’t like an incinerator at their back door. Useful energy *can* be recovered from waste, but the efficiency is low, the carbon emissions are high, the economics are unattractive, and the neighbors can be difficult. Not an entirely rosy picture.

Despite all this, combustion for heat recovery is in some circumstances practical and attractive. The most striking example is the cement industry, one with an enormous energy budget and CO₂ burden because of the inescapable step of calcining in its production. Increasingly, combustion of vehicle tires and industrial

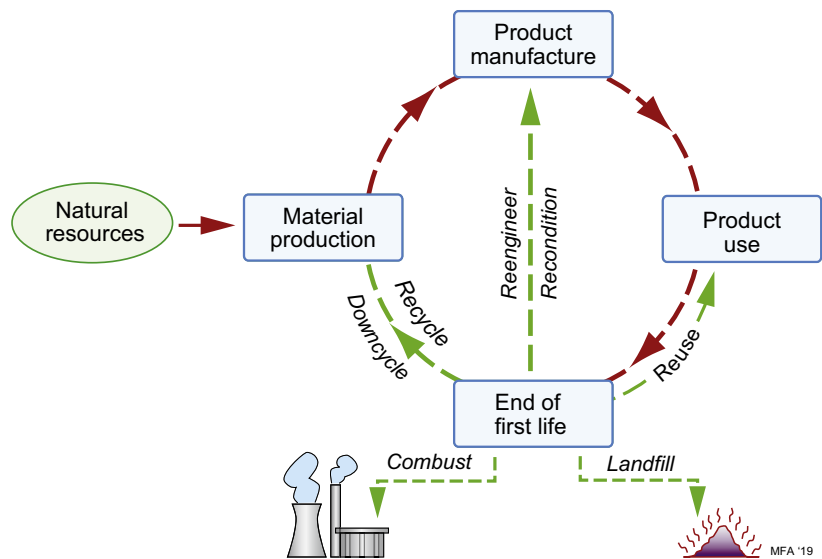


FIGURE 4.1 End-of-life options: landfill, combustion, reengineering or reconditioning, recycling, and reuse.

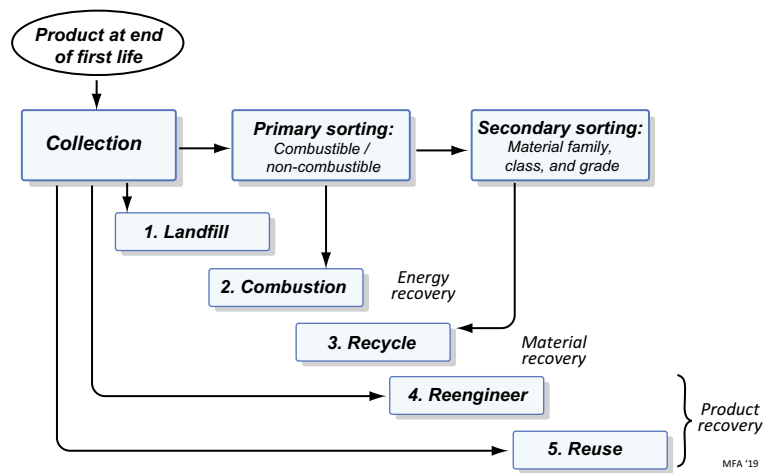


FIGURE 4.2 End-of-life scenarios: landfill, combustion for heat recovery, recycling, reengineering or refurbishment, and reuse. Different levels of sorting and cleaning are required for each.

and agricultural wastes are used as a heat source, reducing the demand on primary fuels, but not, of course, the attendant release of CO₂.

Recycling. Waste is waste only if nothing can be done to make it useful. It can also be a resource. Recycling is the reprocessing of recovered materials at the end of

product life, returning them into the use stream. It is the end-of-life scenario that is best adapted to extracting value from the waste stream.

We return to this in [Section 4.5](#) for a closer look.

Reengineering, reconditioning, restoration. There is the story of the ax—an excellent ax—that, over time, had two new heads and three new handles. But it was still the same ax. Reconditioning, for some products, is cost effective and, compared with total replacement, energy efficient. Aircraft, for instance, don't wear out; instead, replacement of critical parts at regular inspection periods keeps the plane, like the ax, functioning just as it did when it was new. The Douglas DC-3,² an 83-year-old design, is still flying, though not in the hands of its original owners. Premium airlines fly premium aircraft, so older models are sold on to operators with smaller budgets.

Reengineering is the reworking or upgrading of the product or of its recoverable components. Certain criteria must be met to make it practical. One is that the design of the product is fixed—as it is with aircraft once an airworthiness certificate is issued—or that the technology on which it is based is evolving so slowly that there remains a market for the restored product. Here are some examples: housing, office space, road and rail infrastructure; all of these are sectors with enormous appetites for materials. Another example: office equipment, particularly that for printing, copying, and communication. These are services; the product providing them is unimportant to those who need the service so long as it does the job. It makes more sense to lease a service (as we all do with telephone lines, mobile phone and Internet service provision, the provision of fresh water, and much else) because it is in the leasers' interests to maximize the life of the equipment.

Reengineering is not without obstacles. Fashion, style, taste, and perceptions change, making a reconditioned product unacceptable even though it works perfectly well. Personal image, satisfaction, and status are powerful drivers of consumption.

Reuse. The cathedrals of Europe, almost all of them, are built on the foundations of earlier structures, often from the 10th or 11th century, built, in turn, on still earlier 5th- or 6th-century beginnings. If the structure is in a region that was once part of the Roman Empire, then columns, friezes, fragments of the forum, and other structural elements of yet greater antiquity find their way into the structure, too. Reuse is not a new idea, and it is a good one.

Put more formally: reuse is the redistribution of the product to a consumer sector that is willing to accept it in its preowned state, perhaps to reuse for its original purpose (a second hand car, for instance), perhaps to adapt to another (converting the car to a hot rod or a bus into a mobile home).³ The key issue here is that of

²The Douglas DC-3, with a cruise speed of 207 mph and a range of 1500 miles (2400 km), entered service in 1935 and revolutionized air transport in the 1930s and 1940s. Several hundred of them remain in service in 2019.

³What most of us see as waste can become the material of invention to the artist. For remarkable examples of this, visit the Musée International des Arts Modestes, 23 quai du Maréchal de Lattre de Tassigny, 34200 Sète, France (www.miam.org).

communication. Housing estate (realtor) listings and car and boat magazines exist to provide channels of communication for used products. Charity shops pass on clothing, objects, and junk,⁴ acquiring them from those for whom they had become waste and selling them to others who perceive them to have value. The most effective tool ever devised to promote product reuse is probably eBay, successful in this precisely because it provides a global channel of communication.

Newsclip

Plastics sent for recycling are burnt to create fuel. Millions of plastic pots, tubs and trays placed in recycling bins are secretly being incinerated because of lack of specialist facilities to process them.

The Times, May 20, 2019

4.4 The problem of packaging

Few applications of materials attract as much criticism as their use as packaging. The functional life of packaging ends as soon as the package is opened. It is ephemeral, it is trite, it generates mountains of waste, and most of the time it is unnecessary.

Or is it? Think for a moment about the most highly developed form that packaging takes: the way we package ourselves. Clothes provide protection from heat and cold, from sun and rain. Clothes convey information about gender, ethnicity, and religious background. Uniforms identify membership and status, most obviously in the military and the church, but also in other hierarchical organizations: airlines, hotels, department stores, and even utility companies. And at a personal level clothes do much more: they are an essential part of the way we present ourselves. While some people make the same clothes last for years, others wear them only once before—for them—they become “waste” and are given to a charity shop.

Fine, you may say, we need packaging of that sort; but products are inanimate. What’s the point of packaging for them? The brief answer is that products are packaged for precisely the same reasons that we need clothes: protection, information, affiliation, status, and presentation.

So let us start with some facts. Packaging makes up about 18% of household waste, but only 3% of landfill. Its carbon footprint is 0.2% of the global total. Roughly 56% of packaging in Europe and 48% in the United States is recovered and used for energy recovery or recycling. Packaging makes possible the lifestyle we now enjoy. Without it, supermarkets would not exist. By protecting foodstuffs and controlling the atmosphere that surrounds them, packaging extends product life, allows access to fresh products all year round, and reduces food waste in the

⁴A sign above a store in an English town: “We buy junk. We sell antiques.”

supply chain. Tamper-proof packaging protects the consumer. Pack information identifies the product and its sell-by date (if it has one) and gives instructions for use. Brands are defined by their packaging—the Coca-Cola bottle, the Heinz soup can, Kellogg products—essential for product presentation and recognition.

The packaging industry⁵ is well aware of its image problem and strives to improve it by providing maximum functionality with minimum material and replacing plastic with paper. Since 2010, aluminum and plastic beverage containers have been reduced in weight without loss of functionality, with benefits to both business and the environment. The most-used package materials—paper, cardboard, glass, aluminum, and steel—have established recycling markets (see Table 4.1) once they are sorted and cleaned, but much packaging ends up in

Table 4.1 Recycling markets	
Material family	Developed markets for recycled materials
Metals	Steel and cast iron
	Aluminum
	Copper
	Nickel
	Lead
	Titanium
	All precious metals
Polymers and elastomers	Polyethylene terephthalate
	High-density polyethylene
	Low-density polyethylene
	Polypropylene
	Poly(vinyl chloride)
	Polystyrene
Ceramics and glasses	Bottle glass
	Brick
	Concrete and asphalt
Other materials	Cardboard, paper, newsprint

⁵See, for instance, The Packaging Federation, www.packagingfedn.co.uk, or the Flexible Packaging Association, www.flexpack.org.

household waste, the most difficult to sort. Worse, waste packaging accumulates where it is hardest to reach—across the landscape, in rivers, and in the oceans.

So, the bottom line. Legislating packaging out of existence would require major adjustment of lifestyle, greatly increase food waste, and deprive consumers of convenience, product protection, and hygienic handling. The challenge is that of returning as much of it as possible into the materials economy at end of life.

The role of industrial design. What have you discarded lately that still worked or, if it didn't, could have been fixed? Changing trends, promoted by seductive advertising, reinforce the desire for the new and urge the replacement of the old. Industrial design carries a heavy responsibility here—it has, at certain periods, been directed toward creative obsolescence: designing products that are desirable only if new, and urging the consumer to buy the latest models, using marketing techniques that imply that acquiring them is a social and psychological necessity.

But that is only half the picture. A well-designed product can acquire value with age, and—far from becoming unwanted—can outlive its design life many times over. The auction houses and antique dealers of New York, London, and Paris thrive on the sale of products that, often, were designed for practical purposes but are now valued more highly for their aesthetics, associations, and perceived qualities. People do not throw away things for which they feel emotional attachment. So there you have it: industrial design both as villain and as hero. Where can it provide a lead?

When your house no longer suits you, you have two choices: you can buy a new house or you can adapt the one you have got, and in adapting it you make it more personally yours. Houses allow this. Most other products do not. An old product (unlike an old house) is often perceived to be incapable of change and to have such low value that it is simply discarded. That highlights a design challenge: to create products that can be adapted and personalized so that they acquire, like a house, a character of their own and transmit the message, “Keep me, I’m part of your life.” This suggests a union of technical and industrial design that can accommodate evolving technology and at the same time combine quality of material, design, and adaptability to deliver products with lasting and individual character, things to pass on to your children.

4.5 Recycling: resurrecting materials

Of the five end-of-life options shown in Figs. 4.1 and 4.2, only one meets the essential criteria:

- that it can return waste materials into the supply chain and
- that it can do so at a rate that, potentially, is comparable to that at which the waste is generated.

Landfill and combustion fail to meet the first criterion, and reengineering and reuse fail the second. That leaves *recycling*.

Quantification of the process of material recycling is difficult. Recycling costs energy, and this energy carries its burden of emissions. But the *recycle energy* of a material is generally small compared with the initial embodied energy, making recycling—when it is possible—an energy-efficient proposition. It may not, however, be one that is cost efficient. That depends on the degree to which the material has become dispersed. In-house scrap, generated at the point of production or manufacture, is localized and is already recycled efficiently (near 100% recovery). Widely distributed “scrap”—material contained in discarded products—is more expensive to collect, separate, and clean. Many materials cannot be recycled, although they may still be reused in a lower-grade activity; continuous-fiber composites, for instance, cannot yet be re-separated economically into fiber and polymer to reuse them, although they can be chopped and used as fillers. Most other materials require an input of virgin material to avoid buildup of uncontrollable impurities. Thus the fraction of a material production that can ultimately reenter the cycle of Fig. 4.1 depends both on the material itself and on the product into which it has been incorporated.

So how hard is it to recycle materials?

Metals. Metal recycling is highly developed. Metals differ greatly in their density, in their magnetic and electrical properties, and even in their color, making separation comparatively easy. The value of metals, per kilogram, is greater than that of most other materials, making metal recycling economically attractive. There are many limitations on how recycled metals are used, but there are enough good uses that the contribution of recycling to today’s consumption is large.

Polymers. The same cannot be said of polymers. Commodity polymers are cheap, easily processed, and used in large quantities, many in products with small lives but big consequences. Most polymers do not bio-degrade, so they accumulate in landfills. They float in water and are carried downstream to oceans, where they accumulate again, with ecological consequences. All of which, you might think, would encourage effective recycling. But polymers all have nearly the same density, have no significant magnetic or electrical signature, and can take on any color that the manufacturer likes to give them. They can be identified by X-ray fluorescence or infrared spectroscopy, but these are not infallible and they are expensive. Add to this that many polymers are blends and contain fillers, fiber plasticizers, and fire retardants. Add further that the recycling process itself involves a large number of energy-consuming steps. Unavoidable contamination prevents the use of recycled polymers in the product from which they were derived, condemning them to more limited use.

A consequence of this is that the recycling of many commodity polymers is low. Increasing the recycle fraction is a question of identification, and here there is progress. Fig. 4.3 shows, in the top row, the standard recycle marks, ineffective because they do not tell the whole story. The lower row shows the emerging identification system. Here polymer, filler, and weight fraction are all identified. The string, built up from the abbreviations listed in the appendix to this chapter (Section 4.8), gives enough information for effective recycling.

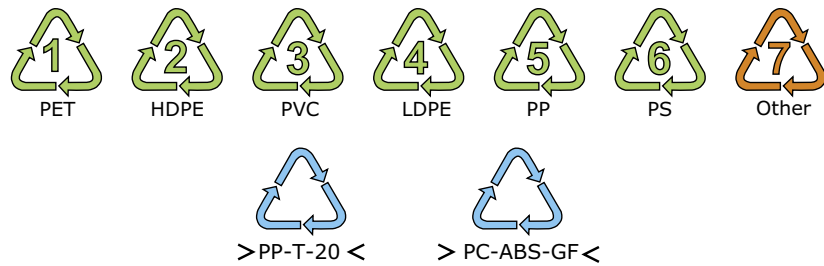


FIGURE 4.3 (Top) Basic recycle marks for commodity polymers. (Bottom) More explicit recycle marks detailing blending, fillers, and reinforcement: polypropylene 20% talc powder and polycarbonate–ABS blend with glass fiber.

Example: identifying polymers. A product contains components with the recycle marks TPA and PMMI-CF-30. What are they?

Answer. Reference to the appendix identifies the first as polyamide thermoplastic elastomer and the second as polymethylmethacrylimide with 30% carbon fiber.

The economics of recycling. Although recycling has far-reaching environmental and social benefits, it is market forces that—until recently—have determined whether it happened. Municipalities collect recyclable waste, selling it through brokers to secondary processors who reprocess the materials and sell them, at a profit, to manufacturers. The recycling market is like any other, with prices that fluctuate according to the balance of supply and demand. In a free market the materials that are recycled are those from which a profit can be made. These include almost all metals but few polymers (Table 4.1).

Scrap arises in more than one way. *New or primary scrap* is the cutoffs from billets, risers from castings, and turnings from machining that are a by-product of the manufacture of products; it can be recycled immediately, often in-house. *Old or secondary scrap* appears when the products themselves reach the end of their useful life (Fig. 4.4). The value of recyclable waste depends on its origin. New scrap carries the highest value because it is uncontaminated and easy to collect and reprocess. Old scrap from commercial sources such as offices and restaurants is more valuable than that from households because it is more homogeneous and needs less sorting.

Producers of secondary materials must, of course, compete with those producing virgin materials. It is this that couples the price of the first to that of the second. Virgin materials command a higher price than those that have been recycled because their quality, in both engineering terms and those of perception, is greater. Manufacturers using recycled materials require assurance that this drop in quality will not compromise their products.

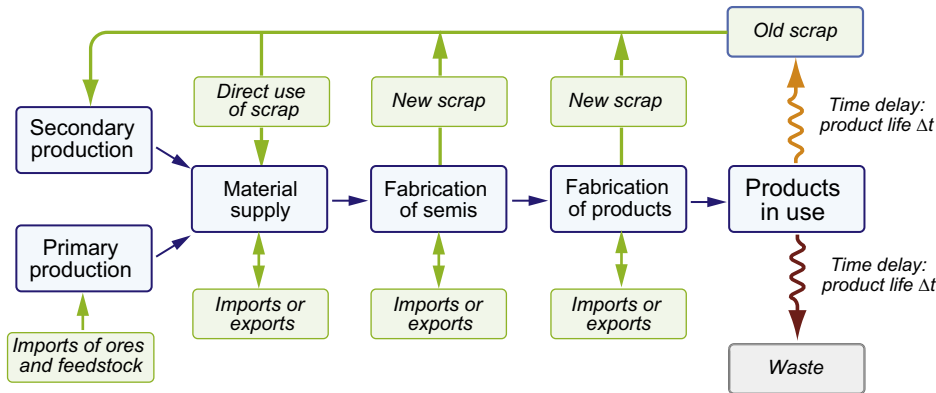


FIGURE 4.4 Material flows, showing recycling paths. New scrap arises during manufacture and is reprocessed almost immediately. Old scrap derives from products at end of life; it reenters production only after a delay of Δt , the product life.

The profitability of a market can be changed by economic intervention: subsidies, for instance, or penalties. Legislation setting a required level of recycling for vehicles, batteries, and electronic products is now in force in Europe; other nations have similar programs and plans for more. Municipalities, too, have recycling laws requiring the reprocessing of waste that, under free market conditions, would have no value. When this is so, municipalities sell the waste for a negative price; that is, they pay processing firms to take it. The negative price, too, fluctuates according to market forces and may turn positive if technology improves or demand increases, removing the need for the subsidy.

Recycling and landfill compete. Landfill, too, carries a cost. What is recycled and what is dumped then changes as market conditions—the level of a landfill tax, for instance—change and businesses seek to minimize the cost of managing waste.

Newsclip

Battery recycling. Nearly 90% of all lead-acid batteries are recycled. Reclaimers crush batteries into nickel-sized pieces and separate the plastic components. They send the plastic to a reprocessor and deliver purified lead to battery manufacturers. A typical lead-acid battery contains 60%–80% recycled lead and plastic.

Illinois University Library, January 24, 2019 (<https://guides.library.illinois.edu/battery-recycling>)

The recycling rate for lead-acid batteries of 90% is exceptional; no other recycled product comes close. Feedstock uniformity and a well-defined, reliable supply chain are essential for successful recycling. Recycling of all other kinds of batteries is difficult and at this writing very limited.

Newsclip: the fluctuating value of waste

Back at junk value, recyclables are piling up. *The economic downturn has decimated the market for recycled materials, leaving more headed for landfills.*

The New York Times, December 8, 2008

The value of recycled materials can go down as well as up, at least in the short term. As landfill charges rise, the economics of recycling become more attractive. But a recycling plant requires investment, and investors do not like unstable markets.

Newsclip

Japan recycles rare earth minerals from used electronics. *Recent problems with Chinese supplies of rare earths have sent Japanese traders and companies in search of alternative sources. [The new source] is not underground, but in what Japan refers to as urban mining—recycling metals and minerals from the country's huge stockpiles of used electronics. Japan's National Institute for Materials Science (NIMS), estimates that used electronics in Japan hold an estimated 300,000 tons of rare earths.*

The New York Times, October 5, 2010

All this may give the impression that waste management is a local issue, driven by local or national market forces. But the insatiable appetite of the fast-developing nations, particularly China and India, turns the “waste” of Europe and the United States into what, for them, is a resource. Low labor costs, sometimes less restrictive environmental regulations, and different manufacturing quality standards drive a global market in both waste and recycled materials. Rising environmental standards in the receiving nations are now choking off this disposal route.

What's in waste? If you want to extract value from waste, it helps to know what's in it. The cover pictures of this chapter show two rather different sorts of waste. They differ in composition (Table 4.2), but both contain useful stuff if it can be isolated. That on the left—municipal waste—holds combustibles, from which heat could be recovered, and organics that could, in principal, be bio-composted for gas. That on the right—electronic waste—contains copper and a range of precious metals and rare-earth elements. As material prices rise and supply chains become uncertain, recovering copper and precious metals from electronic waste becomes increasingly attractive.

Table 4.2 Typical compositions of municipal and electronic waste

US municipal waste	kg/tonne	Electronic waste	kg/tonne
Paper and cardboard	280	Plastics	300
Food waste	150	Glass and ceramics	300
Garden trimmings	130	Copper	200
Plastics	130	Iron	80
Metals	90	Tin	40
Rubber, leather, textiles	80	Silver	2
Wood products	60	Gold	0.6
Glass	50	Palladium	0.1
Other	30	Other	77.3

Newsclip

E-Waste Offers an Economic Opportunity as Well as Toxicity. In 2016, according to the United Nations University, the yearly accumulation (of electronic waste) reached 49.3 million tons. The explosion of e-waste highlights its identity as an environmental scourge and potential economic resource. Though often laced with lead, mercury or other toxic substances, laptops and phones also contain valuable elements like gold, silver and copper. Yet barely 20% of the world's e-waste is collected and delivered to recyclers.

The New York Times, July 5, 2018

The contribution of recycling to current supply. Suppose that a fraction f of the material of a product with a life of Δt years becomes available as old scrap. Its contribution to today's supply is the fraction f of the consumption Δt years ago. Material consumption, generally, grows with time, so this delay between consumption and availability as scrap reduces the fraction that recycling contributes to the supply of today. Fig. 4.5 illustrates this. Suppose, for the moment, that a material exists that is used for one purpose only in a product with a life span Δt and that, at end of life, a fraction f (about 0.6 in the figure) is returned for current consumption, which has been growing at a rate $r_c\%$ per year. If the consumption rate when the product was made (time t_0) was C_0 tonnes per year, then the consumption today, at a later time t^* , is:

$$C = C_0 \exp\left(\frac{r_c}{100}(t^* - t_0)\right) = C_0 \exp\left(\frac{r_c}{100}\Delta t\right) \quad (4.1)$$

where $\Delta t = t^* - t_0$. The recovered fraction R_f is:

$$R_f = fC_0 \quad (4.2)$$

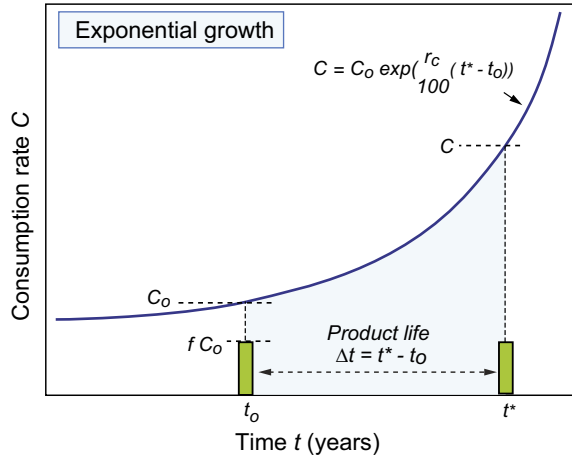


FIGURE 4.5 If consumption grows, long-lived products contribute less to future consumption than those with short lives.

shown as a green bar on the figure. Its fractional contribution to supply today is:

$$\frac{R_f}{C} = \frac{f}{\exp\left(\frac{r_c}{100} \Delta t\right)} \quad (4.3)$$

Fig. 4.6 shows what this looks like for a product with a growth rate of 5% per year. If the fraction $f = 0.6$, and the product life Δt is 1 year, the contribution is large, about 0.58 of current supply (point A on Fig. 4.6). But if the product life is 30 years, the contribution falls to 0.17 (point B). The recycle contribution increases with f , of course. But it decreases quickly if the product has a long life or a fast growth rate. Where consumption is falling (negative r_c), it is even possible for recycling to meet or exceed future needs.

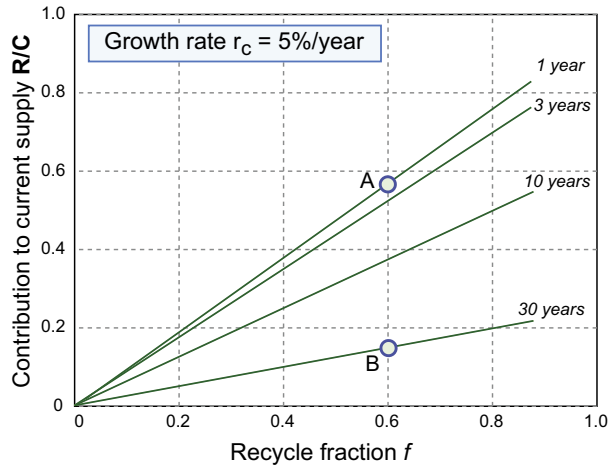


FIGURE 4.6 Recycling effectiveness when the growth rate in consumption is 5% per year, as a function of product life and recycle fraction.

In reality, most materials are used in many products, each with its own life span Δt_i and recycle fraction f_i . Consider one of these—product “ i ”—that accounts for a fraction s_i of the total consumption of the material. Its fractional contribution to supply today is:

$$\frac{R_{f,i}}{C} = \frac{s_i f_i}{\exp\left(\frac{r_c}{100} \Delta t_i\right)} \quad (4.4)$$

where r_c is the overall growth rate of consumption of the material. The total contribution of recycling is the sum of terms like this for the material in all the products that use it.

Example: recycle contribution of gizmos and widgets. A material is used to make both gizmos and widgets. Each accounts for 25% of the total consumption of the material. Gizmos last for 20 years; their sales have grown steadily at 10% per year. At the end of life gizmos are dismantled and all the material is recovered ($f_{\text{gizmo}} = 1$). Widgets, on the other hand, have an average life of 4 weeks and are difficult to collect; their recycle fraction is only $f_{\text{widget}} = 0.5$. Their sales have grown slowly at 1% per year for the recent past. Which contributes most to today’s consumption?

Answer. Inserting these data into Eq. (4.3), we find an unexpected result: gizmos, all of which are recycled, contribute the tiny fraction of 0.03 to the current supply, whereas widgets, only half of which are recycled, contribute a much larger fraction of 0.125.

Products with short lives make larger contributions to supply than those that last for a long time. This reveals one of the many unexpected aspects of the materials economy: making products that last longer can reduce material demand, but it also reduces the scrap available for recycling.

4.6 Summary and conclusions

The greater the number of us who consume and the greater the rate at which we do so, the greater is the volume of materials that our industrial system ingests and then ejects as waste. Waste, potentially, diminishes finite resources, and there has to be somewhere to put it and that, too, is a diminishing resource.

But waste can be seen differently: as a resource. It contains energy and it contains materials, and—since most products still work when they reach the end of their first life—it contains components or products that can still be useful. There are a number of options for treating a product at the end of its first life: extract the energy via combustion, extract the materials and reprocess them, replace the bits that are worn and sell it again, or, simplest of all, put it on eBay or another trading channel and sell it as-is.

All have merit. But only one—recycling—can begin to cope with the volume of waste that we generate and transform it into a useful resource. We return to this in Chapter 6, which provides data, and in Chapter 13 in the discussion of circularity.

4.7 Further reading

Chen, R.W., Navin-Chandra, D., and Prinz, F.B. (1993) “Product design for recyclability: a cost benefit analysis”, Proceedings of the IEEE International Symposium on Electronics and the Environment, Vol. 10–12, pp.178–183. ISEE.1993.302813. *(Recycling lends itself to mathematical modeling. Examples can be found in the book by Chapman and Roberts (above) and in this paper, which takes a cost-benefit approach.)*

Guidice, F. La Rosa, G., and Risitano, A. (2006), “Product design for the environment” CRC/Taylor and Francis, London, UK. *(A well-balanced review of current thinking on eco-design.)*

Hammond, G. and Jones, C. (2010) “Inventory of carbon and energy (ICE), Annex A: methodologies for recycling”, published by The University of Bath, Bath, UK. *(An analysis of alternative ways of assigning recycling credits between first and second lives.)*

Henstock, M.E. (1988) “Design for recyclability”, Institute of Metals, London, UK. *(A useful source of background reading on recycling.)*

Imhoff, D. (2005) “Paper or plastic: searching for solutions to an overpackaged world”, University of California Press. *(What it says: a study of packaging taking a critical stance.)*

PAS 2050 (2008) “Specification for the assignment of the life-cycle greenhouse gas emissions of goods and services”, ICS code 13.020.40, British Standards Institution, London, UK. *(This Publicly Available Specification (PAS) deals with carbon-equivalent emissions over product life, with prescription of the way to assess end of life.)*

Tullo, A.H. (2016) “The cost of plastic packaging”, C&E News, vol. 94 (41). <https://cen.acs.org/articles/94/i41/cost-plastic-packaging.html> *(The author argues that disposable packaging may be justified if it prolongs the shelf-life of high embodied energy foods such as beef.)*

4.8 Appendix: Designations used in recycle marks

(a): Base polymers

E/P	Ethylene—propylene plastic
EVAC	Ethylene—vinyl acetate plastic
MBS	Methacrylate—butadiene—styrene plastic
ABS	Acrylonitrile—butadiene—styrene plastic

ASA	Acrylonitrile—styrene—acrylate plastic
C	Cellulose polymer
COC	Cycloolefin copolymer
EP	Epoxide; epoxy resin or plastic
Imod	Impact modifier
LCP	Liquid-crystal polymer
MABS	Methacrylate—acrylonitrile—butadiene—styrene plastic
MF	Melamine—formaldehyde resin
MPF	Melamine—phenolic resin
PA11	Homopolyamide (nylon) based on 11-aminoundecanoic acid
PA12	Homopolyamide (nylon) based on ω -aminododecanoic acid or on lauro lactam
PA12/MACMI	Copolyamide (nylon) based on PA12,3,3-dimethyl-4,4-diaminodicyclo-hexylmethane and isophthalic acid
PA46	Homopolyamide (nylon) based on tetramethylenediamine and adipic acid
PA6	Homopolyamide (nylon) based on ϵ -caprolactam
PA610	Homopolyamide (nylon) based on hexamethylenediamine and sebacic acid
PA612	Homopolyamide (nylon) based on hexamethylenediamine and dodecane-diacid (1,10-decandicarboxylic acid)
PA66	Homopolyamide (nylon) based on hexamethylenediamine and adipic acid
PA66/6T	Copolyamide based on hexamethylenediamine, adipic acid, and terephthalic acid
PA666	Copolyamide based on hexamethylenediamine, adipic acid, and ϵ -caprolactam
PA6I/6T	Copolyamide based on isophthalic acid, adipic acid, and terephthalic acid
PA6T/66	Copolyamide based on adipic acid, terephthalic acid, and hexamethylenediamine
PA6T/6I	Copolyamide based on hexamethylenediamine, terephthalic acid, adipic acid, and isophthalic acid
PA6T/XT	Copolyamide based on hexamethylenediamine, 2-methylpentamethylenediamine, and terephthalic acid
PAEK	Polyaryl ether ketone
PAIND/INDT	Copolyamide based on 1,6-diamino-2,2,4-trimethylhexane, 1,6-diamino-2,4,4-trimethylhexane, and terephthalic acid
PAMACM12	Homopolyamide based on 3,3'-dimethyl-4,4'-diaminodicyclohexylmethane and dodecanedioic acid
PAMXD6	Homopolyamide based on <i>m</i> -xylylenediamine and adipic acid

PBT	Poly(butylene terephthalate)
PC	Polycarbonate
PCCE	Poly(cyclohexane dicarboxylate)
PCTA	Poly(cyclohexylene dimethylene terephthalate) acid
PCTG	Poly(cyclohexylene dimethylene terephthalate) glycol
PE	Polyethylene
PEI	Polyetherimide
PEN	Poly(ethylene naphthalate)
PES	Polyethersulfone
PET	Poly(ethylene terephthalate)
PETG	Poly(ethylene terephthalate) glycol
PF	Phenol—formaldehyde resin
PI	Polyimide
PK	Polyketone
PMMA	Poly(methyl methacrylate)
PMMI	Polymethylmethacrylimide
POM	Polyoxymethylene, polyacetale, polyformaldehyde
PP	Polypropylene
PPE	Poly(phenylene ether)
PPS	Poly(phenylene sulfide)
PPSU	Poly(phenylene sulfone)
PS	Polystyrene
PS-SY	Polystyrene, syndiotactic
PSU	Polysulfone
PTFE	Polytetrafluoroethylene
PUR	Polyurethane
PVC	Poly(vinyl chloride)
PVDF	Poly(vinylidene fluoride)
SAN	Styrene—acrylonitrile plastic
SB	Styrene—butadiene plastic
SMAH	Styrene—malefic anhydride plastic
TEEE	Thermoplastic ester and ether elastomers
TPA	Polyamide thermoplastic elastomer
TPC	Copolyester thermoplastic elastomer
TPO	Olefinic thermoplastic elastomer
TPS	Styrenic thermoplastic elastomer
TPU	Urethane thermoplastic elastomer

TPV	Thermoplastic rubber vulcanisate
TPZ	Unclassified thermoplastic elastomer
UP	Unsaturated polyester

(b): Fillers

CF	Carbon fiber
CD	Carbon fines, powder
GF	Glass fiber
GB	Glass beads, spheres, balls
GD	Glass fines, powder
GX	Glass not specified
K	Calcium carbonate
MeF	Metal fiber
MeD	Metal fines, powder
MiF	Mineral fiber
MiD	Mineral fines, powder
NF	Natural organic fiber
P	Mica
Q	Silica
RF	Aramid fiber
T	Talcum
X	Not specified
Z	Others not included in this list

4.9 Exercises

E4.1. *Why waste?* Many products are thrown away and enter the waste stream even though they still work. What—as much as possible in your own words—are the reasons for this?

E4.2. *Eliminating waste.* Is waste inevitable in a manufacturing economy? If yes, why? If no, give an example of a manufacturing process that is waste free.

E4.3. *Disposal paths.* What options are available for coping with the waste stream generated by modern industrial society?

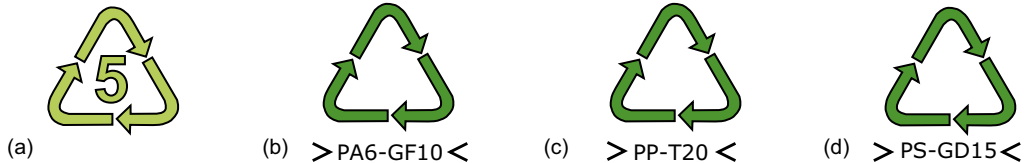
E4.4. *Recycling.* Recycling has the attraction of returning materials into the use stream. What are the obstacles to recycling?

E4.5. Innovative disposal. Vehicle tires create a major waste problem. Use the Internet to research ways in which the materials contained in car tires can be used, either in the form of the tire or in some decomposition of it.

E4.6. Packaging (1). List three important functions of packaging.

E4.7. Packaging (2). As a member of a brain-storming group you are asked to devise ways of reusing polystyrene foam packaging—the sort that encases TV sets, computers, appliances, and much else when transported—most of which at present is sent to landfill. Use free thinking: no suggestion is too ridiculous.

E4.8. Recycle codes. You are employed to recycle German washing machines, separating the materials for recycling. You encounter components with the following recycle marks:



Use the codes listed in the appendix (Section 4.8) of Chapter 4 to interpret them.

E4.9. Effective recycling. The consumption of *lead* is growing at 4% per year. It has a number of uses, principally as electrodes in storage batteries, as roofing and pipework on buildings, and as pigment for paints. The first two of these allow recycling, the third does not. Car batteries consume 38% of all lead, have an average life of 4 years, have a growth rate of 4% per year, and are recycled with an efficiency of 80%. Architectural lead accounts for 16% of total consumption. The lead on buildings has an average life of 70 years, after which 95% of it is recycled. What is the fractional contribution of recycled lead from each source to the current supply?

E4.10. Electronic waste (1). The world sales of smartphones in 2017 were 1.54 billion units. The average smartphone weighs 150 g and has a composition corresponding to that for electronic waste listed in Table 4.2 of the text. How much gold is required for the 2017 production of smartphones?

E4.11. Electronic waste (2). The average smartphone has a life of 3 years. Smartphone sales are increasing at $r = 3.3\%$ per year.

- (a) The global smartphone sales in 2017 were $C_0 = 1.54$ billion. What are the anticipated sales C in 2020?
- (b) If 15% of the gold content of waste smartphones can be recovered, what fraction of the gold for the 2020 production can be met?

E4.12. Self-sufficiency (1). A nation imports a material M to manufacture a single family of products with an average life of Δt years and a production

growth rate of r_c % per year. The material is not at present recycled at end of life but it could be. The government is concerned that imports should not grow.

- (a) What recycle fraction, f_{crit} , is necessary to make this possible?
- (b) The longer the average product life, Δt , the less is its fractional contribution to the future supply. What is the limiting life beyond which recycling cannot keep up with increased demand?

E4.13. *Self-sufficiency (2).* Hybrid and electric car production is currently growing at $r = 31\%$ per year worldwide. The cars have an average life of $\Delta t = 13$ years. The rare-earth metal *neodymium* is an ingredient of high-field permanent magnets at present used for their motors. If $f = 80\%$ of the neodymium in these motors can be recovered at end of life, what fraction of future neodymium demand for car motors can be met?

The long reach of legislation



CONTENTS

- 5.1 Introduction and synopsis
- 5.2 Growing awareness and legislative response
- 5.3 International treaties, protocols, conventions, agreements, and standards
- 5.4 National legislation: directives, acts, and laws
- 5.5 Economic instruments: taxes, subsidies, and trading schemes
- 5.6 The legislative burden
- 5.7 Summary and conclusions
- 5.8 Further reading
- 5.9 Exercises

5.1 Introduction and synopsis

The prophet Moses, seeking to set standards for the ways in which his people behaved, created or received (according to your viewpoint) 10 admirably concise commandments. Most start with the words “Thou shalt not ...,” with simple, easily understood incentives (heaven, hell) to comply. Today, as far as materials and design are concerned, it is environmental protection agencies and European commissions that issue commandments, or, in their language, *regulations* and *directives*. The consequences of ignoring them are not as Old Testament in their severity as those of the original 10, nor are they as concise, but if you want to grow your business, compliance becomes a priority.

Warning signs that relate to materials. Clockwise from the top left: Highly flammable, Corrosive, Poisonous, Landfill ban, Water-polluting, Air-polluting.

This involves some obvious steps:

- being aware of directives or other binding controls that touch on the materials or processes you use;
- understanding what is required to comply with them;
- having (or developing) tools to make compliance as painless as possible;
- exploring ways to make compliance profitable rather than a burden—exploiting compliance as a marketing tool, for example.

This chapter is about controls and economic instruments that impinge on the use of engineering materials. It reviews current legislation and describes examples of tools to help with compliance.

5.2 Growing awareness and legislative response

Table 5.1 lists 11 documents that have had profound influence on current thinking about the effects of human activity on the environment. The publications span a little less than 60 years. Over this period, the response of industry to a pollution or environmental problem has evolved through a number of phases,¹ best summarized in the following way:

- *Ignore it*: Pretend it isn't there.
- *Dilute it*: Make the smokestack taller, or pump it farther out to sea.
- *Fix it with as little disruption of production as possible*: The “end-of-pipe” approach.
- *Prevent it in the first place*: The first appearance of design for the environment.
- *Aim for sustainability*: Seek ways to establish equilibrium with the environment—the phase we are in now.

Today, national legislation and international protocols and agreements set environmental standards. The international agreements tend to be broad statements of intent. The national legislation, by contrast, tends to be specific and detailed.

Historically, environmental legislation has targeted isolated problems as they arose—dumping of toxic waste, sewage in water, lead in petrol, ozone depletion in the atmosphere—taking a *command and control* approach: “thou shalt not” cast in modern terms. There is a growing recognition that this can lead to perverse effects whereby action to fix one isolated problem just shifts the burden elsewhere and may even increase it. For this reason there has been a shift from command and control legislation toward the use of *economic instruments*—green taxes, subsidies, trading schemes—that seek to use market forces to encourage the efficient use of materials and energy. We have already seen that some activities create environmental burdens that have costs that are not paid for by the provider or user.

¹Details can be found in books on industrial ecology such as Ayres and Ayres (2002)—see “Further reading”.

Table 5.1 Landmark publications

Date, author, and title	Subject
1962 Rachel Carson, <i>Silent Spring</i>	Meticulous examination of the consequences of the use of the pesticide DDT and of the impact of technology on the environment
1972 Club of Rome, "Limits to Growth"	The report that triggered the first of a sequence of debates in the 20th century on the ultimate limits imposed by resource depletion
1972 The Earth Summit in Stockholm	The first conference convened by the United Nations to discuss the impact of technology on the environment
1987 The UN World Commission on Environment and Development, "Our common future"	Known as the Brundtland Report, it defined the principle of sustainability as "Development that meets the needs of today without compromising the ability of future generations to meet their own needs"
1987 Montreal Protocol	The International Protocol to phase out the use of chemicals that deplete ozone in the stratosphere
1992 Rio Declaration	An International statement of the principles of sustainability, building on those of the 1972 Stockholm Earth Summit
1998 Kyoto Protocol	An international treaty to reduce the emissions of gases that, through the greenhouse effect, cause climate change
2001 Stockholm Convention	The first of a series of meetings to agree on an agenda for the control and phase-out of persistent Organic Pollutants
2007 IPCC 4th Assessment Report, "Climate change 2007—the physical basis"	This Report of the Intergovernmental Panel on Climate Change establishes beyond any reasonable doubt the correlation between carbon in the atmosphere and climate change
2015 The Paris Agreement	The Paris Agreement, adopted by 195 nations, resolved to hold the global average temperature to below 2°C above preindustrial levels
2018 The Incheon Report	The Paris Agreement included a commitment to further reports. This, the first, urged a downward revision of the threshold from 2°C to 1.5°C, recognizing that this would require "rapid, far-reaching and unprecedented changes in all aspects of society"

These are called external costs or *externalities*. A more effective approach is to transfer the cost back to the activity creating it, thereby *internalizing* it. But that is not always easy, as we shall see.

5.3 International treaties, protocols, conventions, agreements, and standards

It is exceedingly difficult to negotiate enforceable treaties that bind all the nations of the planet to a single course of action; the differences of culture, national priorities, economic development, and wealth are too great. The best the international community can achieve is an agreement, declaration of intent, or protocol² that a subset of nations feels able to sign. Such agreements directly influence policy in the nations that sign them. By defining the high ground, they exert moral pressure on both on signatories and nonsignatories alike. Three have been particularly significant in their influence on government policy on materials.

The Montreal Protocol (1989) is a treaty aimed at reducing the use of substances that deplete the ozone layer of the stratosphere. Ozone depletion allows more UV radiation to reach the surface of the earth, damaging living organisms. The culprits are typified by CFCs—chlorofluorocarbons—that were widely used as refrigerants and as blowing agents for polymer foams, particularly those used for house insulation. All have now been replaced by less harmful substitutes. The protocol has largely achieved its aims.

The Kyoto Protocol (1997) is an international treaty to reduce the emissions of gases that, through the greenhouse effect, cause climate change. It set binding targets for the 44 industrialized countries that have signed it, committing them to reduce greenhouse gas emissions over the 5-year period 2008–12.

The Paris Agreement (2015), adopted by 195 nations, resolved to limit the rise in global average temperature to less than 2°C above preindustrial levels. It is seen as a bridge between today's policies and climate neutrality before the end of the century. The participating governments agreed:

- to aim to limit the increase to 1.5°C, since this would significantly reduce risks and the impacts of climate change;
- on the need for global emissions to peak as soon as possible, recognizing that this will take longer for developing countries;
- to undertake rapid reductions thereafter in accordance with the best available science.

²A protocol is a memorandum of resolutions arrived at in negotiation, signed by the negotiators, as a basis for a final convention or treaty. In fact, the Kyoto Protocol is more than that, being a binding treaty to meet certain agreed-upon objectives. The distinction between the protocol and the convention, in current usage, is that while the convention encourages countries to stabilize emissions, the protocol commits them to do so.

Newsclip: Trump Will Withdraw U.S. From Paris Climate Agreement.

President Trump announced on Thursday that the United States would withdraw from the Paris climate accord, weakening efforts to combat global warming and embracing isolationist voices in his White House who argued that the agreement was a pernicious threat to the economy and American Sovereignty.

***New York Times*, June 1, 2017**

Newsclip: World is woefully short of 2-degree goal for climate change.

According to a United Nations report released Tuesday, projected emissions of carbon dioxide, the primary greenhouse gas, from nations around the world fall woefully short of the 2-degree Celsius set in the Paris Climate Agreement in 2015.

***CNN-World*, November 28, 2018**

Newsclip: Renewable don't work, says US President.

Trump refuses to reverse his position on the 2016 Paris agreement limiting global warming to 1.5 C.

***The Sunday Times*, June 30, 2019.**

Getting 195 nations to agree on something is not simple.

International directives and protocols are based on *principles*—statements of fundamental rights—rather than on laws that cannot be agreed upon or enforced. They exert moral rather than legal pressure. Here are five that have emerged from the protocols and conventions of [Table 5.1](#):

- *Principle 1* (Stockholm Declaration): The right to exploit one's own environment.
- *Principle 2* (Rio Declaration): The right to industrial development provided it does not damage others.
- *Precautionary principle* (World Commission on Environment and Development report): Where there are possibilities of large irreversible impacts, the lack of scientific certainty should not prevent preventative action from being taken.
- *Polluter pays principle*: Responsibility and cost of pollution rests with the polluter.
- *Sustainable development principle*: Protection of the environment, equity of burden.

These are now widely accepted (though not by all) as a framework within which strategies and actions are developed. In Europe, for example, much legislation is based on the precautionary principle, but this is invoked less frequently in the United States.

Standards. ISO 14000 of the International Organization for Standardization (ISO) defines a family of standards for environmental management systems.³ It contains the set ISO 14040, 14041, 14042, and 14043 published between 1997 and 2000, prescribing broad but vague procedures for the four steps described in Chapter 3, Section 3.4 (*goals and scope, inventory compilation, impact assessment, and interpretation*). The standard is an attempt to bring uniform practice and objectivity into life-cycle assessment (LCA) and its interpretation, but it is not binding in any way.

ISO 14025 is a standard guiding the reporting of LCA data as an environmental product declaration (EPD)⁴ or a climate declaration (CD)⁵ (there is an example in Chapter 8, Section 8.7). The EPD describes the output of a full LCA—a considerable task. To make it a little easier, the CD is limited to emissions that contribute to global warming: CO₂, CO, CH₄, and N₂O. But it is still a big job.

PAS2050⁶ (2008) is an attempt to reduce the burden further. It focuses on greenhouse gas emissions of goods and services. It is a consultative document, not, at present, a standard, but it is increasingly accepted by the manufacturing industry in Europe as an acceptable product assessment.

In practice, LCAs are used primarily for in-house product development, for benchmarking, and to promote the environmental benefits of one product over another. They are rarely used as the basis for regulation because of the difficulties, described in Chapter 3, of setting system boundaries, of double counting, and of limited coverage across products.

5.4 National legislation: directives, acts, and laws

The Council of the European Union, having regard to A, B and C, acting in accordance with procedures P, Q and R of activities X, Y and Z, and whereas ... (there follows a list of 27 further “whereases”) HAS ADOPTED THIS DIRECTIVE

That was a paraphrase of the start of an EU directive. Environmental legislation makes heavy reading. It is cast in legal language of such Gothic formality and baroque intricacy that organizations spring up with the sole purpose of interpreting it. But since much of it impinges, directly or indirectly, on the use of materials, it is important to get the central message.

National legislation, as typified by the US Environmental Agency acts or the European Union environmental directives, takes four broad forms:

- setting standards;
- negotiating voluntary agreements with industry;

³See www.iso-14001.org.uk/iso-14040 for a summary.

⁴<https://www.environdec.com/What-is-an-EPD/>.

⁵For the more intimate details, see www.environdec.com.

⁶PAS stands for Publicly Available Specification.

- imposing binding legislation, with penalties if its terms are not met;
- devising economic instruments that harness market forces to induce change: taxes, subsidies, and trading schemes.

Voluntary agreements and binding legislation. Current legislation is aimed at internalizing environmental costs and conserving materials by increasing manufacturers' responsibilities, placing on them the burden of cost of disposal. There are a lot of them, so take a deep breath. We'll keep it brief.

US legislation. The US Environmental Protection Agency (EPA) is tasked with monitoring and enforcing environmental legislation.

The US Resource Conservation and Recovery Act (RCRA) of 1976 is a federal law of the United States. The RCRA's goals are:

- to protect the public from harm caused by waste disposal;
- to encourage reuse, reduction, and recycling;
- to clean up spilled or improperly stored wastes.

The US EPA 35/50 Program (2016) identified 31 priority chemicals with the aim of reducing industrial toxicity by voluntary action by industry. It includes the heavy metals lead, cadmium, and mercury and their compounds, together with many volatile organic compounds (VOCs), such as benzene and carbon tetrachloride, widely used as solvents.

The Toxic Substances Control Act,⁷ enacted by Congress in 1976, regulates the introduction of new or existing chemicals. Like the European REACH legislation, the act gives the EPA the power to assess new chemicals before they enter the market and to regulate those that pose an "unreasonable risk to health or to the environment." The act was amended in 2016 to allow the EPA to evaluate existing chemicals and impose enforceable deadlines for their removal from the market.

The US EPA Code of Federal Regulation deals with protection of the environment and human health, imposing restrictions on chemicals released into the environment during manufacture, life, and disposal. Like REACH (discussed later), it requires manufacturers to register the use of a long list of chemicals and materials (Table 302.2 of the regulation) if the quantity used exceeds a defined threshold.

Newsclip: Trump's IPA pivots again on reviews of new chemicals under TSCA.

Political appointees at the Environmental Protection Agency (EPA) are on the verge of taking yet another huge lurch away from the 2016 reforms to the Toxic Substances Control Act (TSCA).

Environmental Defense Fund, July 17, 2018

Environmental legislation is not immune to political influence.

⁷<http://www.epa.gov/>.

European legislation. The European Union imposes a similar catalog of restrictions, enacted as directives.

Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) (2006) requires manufacturers to manage risks from chemicals and to find substitutes for those that are most dangerous. The list of restricted substances is long—it has some 30,000 entries. Here are just a few examples of restrictions that affect materials. Some are draconian: a total ban. Others are mild: keep it below 0.1% in things for children:

- asbestos (prohibited)
- flame retardant compounds (limit 0.1%)
- arsenic compounds (prohibited in wood products)
- cadmium compounds (0.25% in galvanization, 0.01% in electronics)
- chromium, hexavalent compounds (limited to 0.1% in electronics)
- lead compounds (limit 0.1% in electronics)
- mercury compounds (limit 0.1% in electronics)
- nickel compounds (limit on articles in prolonged contact with skin)
- organostannic (tin) compounds (limit 0.1% in products)
- ozone-depleting bromochloromethanes, CFCs, halons, solvents (prohibited)
- phthalate plasticizers (toys and childcare limit of 0.1%)
- hydrocarbon solvents (limit 0.1% in products)

Many polymers contain flame retardants or plasticizers. Chromium plating involves hexavalent chromium. Ordinary solder contains lead. Rechargeable batteries contain cadmium, and long-life, low-drain batteries contain mercury. Nickel is a component of resistors, heating elements, and magnets. Many manufacturing processes involve the use of organic solvents.

The trouble, if you make things, is that you have to check for all restricted substances to avoid getting into trouble. Carmakers are value-added resellers; they assemble vehicles using parts from independent original equipment manufacturers, so the entire supply chain must conform to REACH. The motive of the directive is to be respected, but compliance is burdensome.

Newsclip: Manufacturers unaware of chemical legislation REACH
***BusinessGreen*, January 14, 2011**

The business journal mounts an awareness campaign to bring REACH to the attention of product makers.

There are many more EU directives that influence the choice of materials. Here, briefly, are some of them.

The Product Liability Directive (1985) imposes liability responsibility for damage caused by defective products.

The Landfill Directive (1999) sets rules for dealing with hazardous and nonhazardous wastes, banning the landfilling of many products, among them tires.

The Volatile Organic Compounds (VOC) Directive (1999) limits the emissions of VOCs from organic solvents in paints and cleaning fluids.

End-of-Life Vehicles (ELV) Directive (2000) sets norms for recovering materials from dead cars. The initial target was that 80% by weight must be recycled or reused. In 2015, the target was raised to 95%. The idea is to encourage redesign to maximize ease of disassembly.

Restriction of Hazardous Substances (RoHS and RoSH2) Directive (2002 and 2011) bans the sale of new electrical and electronic equipment containing more than set levels of lead, cadmium, mercury, hexavalent chromium (used in pigments, paints, and electroplate), and various flame retardants.

Waste Electrical and Electronic Equipment (WEEE, 2002) sets collection, recycling, and recovery targets for electrical goods. Producers must pay for the collection, recovery, and safe disposal of their products and meet certain recycling targets.

The Energy-Using Products (EuP, 2003) **and** ***Energy-Related Products*** (2009) **Directives** impose eco-design requirements for products that use energy—appliances, electronic equipment, pumps, motors, and the like—and for products that are energy related even if they don't use it—double glazing, faucets, and showers, for example. It requires that manufacturers “shall demonstrate that they have considered the use of energy in their product as it relates to materials, manufacture, packaging transport and distribution, use, and end of life.”

The Battery Directive (2006) bans the sale of batteries containing more than 0.0005% mercury or 0.002% cadmium, prohibits the dumping or incineration of batteries, and requires that they be collected and recycled.

Waste Framework Directive (WFD, 2008) sets criteria for waste management: prevention, reuse, recycling, and energy recovery. Those generating waste must keep records of the quantity, origin, and destination, and must pay for it (the “polluter pays” principle).

The United States and Europe are not the only nations with legislation that influences the use of materials. India⁸ and China,⁹ the world's two most populous nations, now have extensive acts and laws to control industrial pollution, as do most Asian and South American countries. Fig. 5.1 gives an idea of the scale of it all. If products are made in a nation, they must meet the environmental restrictions of that nation. Equally important in an era of global trade, if products are exported, they must also comply with the legislation of the nation to which they are sent.

Fuel economy standards. The legislation that has had the greatest impact on material choice is probably that requiring greater fuel efficiency and lower carbon emissions from vehicles.

⁸[https://uk.practicallaw.thomsonreuters.com/0-503-2029?transitionType=Default&contextData=\(sc.Default\)](https://uk.practicallaw.thomsonreuters.com/0-503-2029?transitionType=Default&contextData=(sc.Default)).

⁹[k.practicallaw.thomsonreuters.com/3-503-4201?transitionType=Default&contextData=\(sc.Default\)&firstPage=true&bhcp=1](https://k.practicallaw.thomsonreuters.com/3-503-4201?transitionType=Default&contextData=(sc.Default)&firstPage=true&bhcp=1).

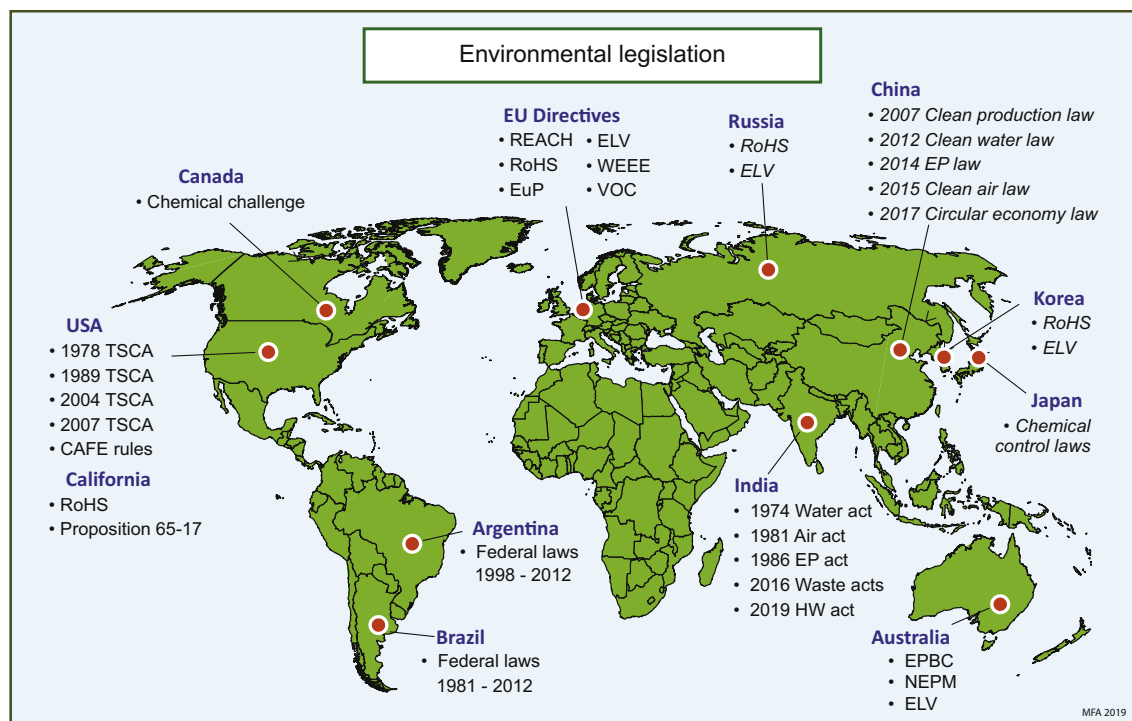


FIGURE 5.1 Some of the global environmental legislation.

The Arab oil embargo of 1973/74 created a spike in oil prices and the realization that dependence on imported oil carried risks. It stimulated the US Congress to pass the Energy Policy Conservation Act of 1975, establishing the Corporate Average Fuel Economy (CAFE) standards and penalties and credits for the average fleet fuel consumption for each carmaker. “Fleet” means all the cars, of all sizes, sold by a carmaker in a given model year. The motive was to raise the fuel efficiency of new cars sold in the United States from an average of around 15 mpg (miles per US gallon¹⁰) to 27.5 mpg by 1985. The Energy Independence and Security Act, passed 32 years later (2007), raised the bar, aiming for a progressive increase to 35 mpg by 2020. The Obama administration mandated a progressive rise to 47 mpg by 2025, but his successor in the White House locked it at the 2020 target of 37 mpg (Fig. 5.2). Failure to achieve it incurs a penalty of \$55 per mpg per car below target. Exceeding the target creates a corresponding credit that can be set against penalties in adjacent years. The sums of money involved are large: between 1983 and 2010, manufacturers paid more than \$500 million in penalties to the US government.

¹⁰1 mpg_{US} = 1.2 mpg_{Imperial} = 0.245 L/100 km.

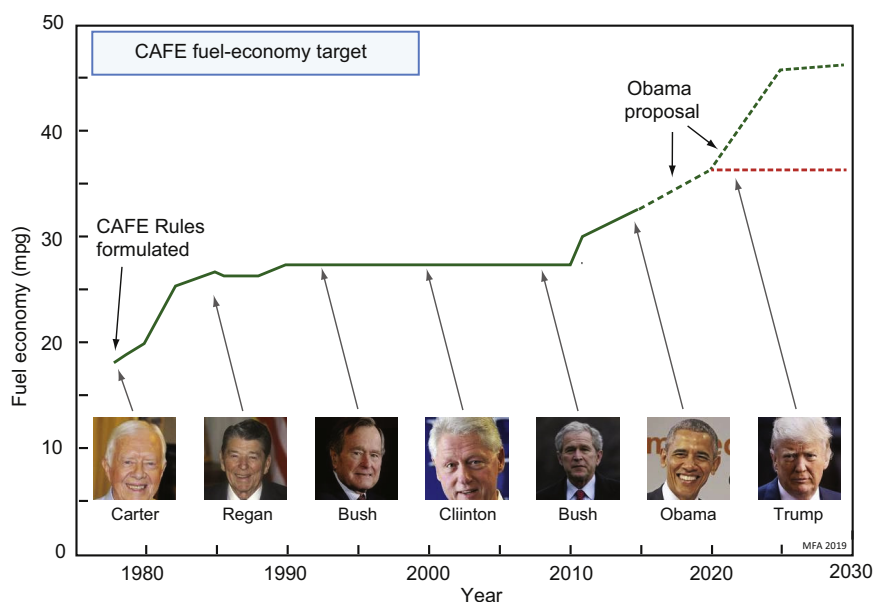


FIGURE 5.2 *The CAFE target over time, illustrating the differing priorities of successive US administrations. (Images of US presidents courtesy Wikipedia).*

The CAFE rules and their equivalents in other nations have driven big changes in the way materials are used in cars. New steels, aluminum and magnesium alloys, and carbon-fiber composites are increasingly used to reduce weight and thus fuel consumption. Concern about carbon and NO_x emissions in cities have further stimulated the take-up of hybrid and electric vehicles, creating demand for the elements used in batteries and in high-field magnets (lithium, cobalt, neodymium, praseodymium). Autonomous vehicles, with the promise of new business models for personal transport, increase demand for functional materials, many of which use elements rare enough to be classed as “critical.”

Why would automakers choose to pay millions of dollars in penalties when, by reducing weight and engine size, they could avoid it? It is because it is more profitable for premium marks to give the customers what they want (size, power, luxury) and pay the penalty than it is to damage the brand by failing to meet expectations. If, as an example, the fleet economy lies a full 2 mpg below the CAFE target, the penalty per car is a little over \$100, which can be passed on to the purchasers without them feeling pain. By contrast, that same 2 mpg difference in fuel economy translates, over a vehicle life of 150,000 miles, into an additional 430 gallons of fuel, which, at \$4 per gallon, costs \$1700. Simple economics thus suggests that

fuel price should be a more powerful driver for fuel economy than the CAFE standard, but because fuel cost is spread over life, it may not appear so.

Newsclip: Automakers in the crosshairs as Democrats head for Congress.

Few recent administrations have taken as many steps as Trump's that directly impact automotive manufacturers and suppliers, autoworkers and auto buyers. Sometime in the coming weeks, the Trump Administration will announce final plans for rolling back the Corporate Average Fuel Economy, or CAFE, standards considered one of the signature accomplishments of the preceding Obama White House.

CNBC, November 11, 2018.

5.5 Economic instruments: taxes, subsidies, and trading schemes

"Economic instruments manipulate market forces to influence the behaviour of consumers and manufacturers in ways that are subtler and more effective than conventional controls, and they generally do so at lower cost" (UK Department of the Environment, 2011). Well, that's the idea. One "economic instrument"—taxation—may not strike you as subtle,¹¹ but it does seem to work better than "command and control" methods. Here are some examples.

Green taxes. Many countries impose a *landfill tax*, averaging about \$30 per tonne in the United States, €70 per tonne in Europe, and £90 per tonne in the United Kingdom, as a tool to reduce waste and encourage better waste management. An *aggregate tax* on gravel and sand, about €2 (\$2.3) per tonne, is designed to reduce the use of virgin aggregate and stimulate the use of waste from construction and demolition. Most nations impose a *fuel duty*—a tax on gasoline and diesel fuel—to encourage a shift to fuel-efficient vehicles and increase the use of bio-fuels by taxing them at a lower rate. Increasingly, governments impose a *carbon tax* on carbon dioxide emissions (at present £18 per tonne in the United Kingdom, €20 per tonne in parts of Europe, and \$11 per tonne in parts of the United States) and *emission taxes* on emissions of NO_x and SO_x. Roughly half the US states charge a deposit—a returnable tax—on bottles and cans, a scheme that has proved effective in returning these into the recycling loop.

But imposing a tax, a carbon tax, for instance, has two difficulties. First, it does not guarantee the environmental outcome of reducing CO₂; industries that can afford it will simply pay it. The second is one of public acceptance. Taxes carry high administration costs, and people don't trust governments to spend the tax on the environment; fuel taxes, for example, don't get spent on roads or

¹¹"Nothing is certain but death and taxes." Benjamin Franklin, writing 250 years ago.

pollution-free vehicles. And of those two certainties of life—death and taxes—it is taxes that people try hardest to avoid.

Newsclip: Externalized costs. The controversial idea of a carbon tax in Europe resurfaces.

A mandate now before the European Commission proposes a tax of at least 20 euros/tonne on carbon emissions from homes, transport and agriculture but not on the industrial sectors already covered by carbon-trading legislation.

Le Monde, April 8, 2011

A carbon tax is more effective than an energy tax because it disadvantages only energy from fossil fuels. At this writing, only a few countries have a carbon tax (Sweden, Denmark, Finland, Ireland, and the United Kingdom). The European Commission meeting was set up to make it Europe-wide. The meeting did not result in agreement. France saw it as disadvantageous to its agriculture. Germany saw it as impeding the expansion of its automobile sector. There is still no Europe-wide carbon tax.

Subsidies. If people don't do what you want, you can try paying them to change their minds. Most developed nations at present subsidize the building of wind and solar farms to generate low-carbon power, motivated by commitments they have made to reduce greenhouse gas emissions. The motive is to kick-start these industries, at present uneconomic, relying on technical and economic developments that will make them viable without state support in the future. The essential ingredient is consistency: offering a subsidy 1 year and canceling it the next undermines investor confidence in a nascent manufacturing base before it has had time to become established.

Newsclip: Slippery subsidies. "Subsidy review dims solar hopes.

The future viability of Britain's biggest solar power schemes has been thrown into doubt by government proposals to cut their public subsidy.

The Financial Times, March 19, 2011

Wind power suffered a similar fate.

The car industry has had a similar history. As an incentive to reduce carbon emissions, cars emitting less than 100 g/km were taxed less heavily or not at all. But not for long. The subsidy was transferred to hybrid and fully electric vehicles, taking the form of a cash refund of around 10% of the purchase price. Today only fully electric vehicles command a subsidy, opposed by many on both economic and social grounds.

Subsidies carry the risk that they remove incentive to increase efficiency by allowing producers to market products that, without a subsidy, would be uneconomic.

Newsclip: Congress should end electric car subsidies, not expand them.

Car buyers can qualify for up to \$7,500 in government subsidies when buying an electric vehicle. The EV tax credit is anti-competitive and prevents the free market from operating correctly. Most beneficiaries are high-income individuals, while the costs of these subsidies are disproportionately borne by lower-income consumers, for whom the cost of owning an electric car is prohibitive.

The Hill, November 27, 2018.

Newsclip: Hybrid car sales fall after green subsidies slashed.

The number of eco-friendly cars sold in Britain has fallen for the first time after the government cut subsidies.

The Times, July 5, 2019.

Trading schemes. Another way of putting a value on something is to create a market for it. The stock market is an example: a company issues shares, the total number of which represents its “value.” The shares are traded—sold or purchased for real money—and they therefore float in value, rising if they are seen as undervalued, falling if they are seen as overpriced. At any moment in time the share price sets a value on the company. A notion emerging from the Kyoto Meeting of 1987 was to adapt this “market principle” to establish a value for emissions. To see how it works and the difficulties with it, we need to digress to explore emissions trading.

Emissions trading is a market-based scheme that allows participants to buy and sell permits for emissions or credits for reduction in emissions in certain pollutants. Taking carbon (meaning CO₂) as an example, the regulator first decides on a total acceptable emissions level and divides this into tradable units (like shares) called *permits*, trading at the moment at €19 per permit. These are allocated to the participants, based on their actual carbon emissions at a chosen point in time. The actual carbon emissions of any one participant change with time, falling if they develop more efficient production technology or rising if they increase capacity. A company that emits more than its allocated permits must purchase allowances from the market, while a company that emits less than its allocations can sell its surplus. Unlike regulation that imposes emission limits (the “command and control” approach), emissions trading gives companies the flexibility to develop their own strategy to meet emission targets. The environmental outcome is not affected because the total number of permits is fixed or is reduced over time as environmental concerns grow. The buyer is paying a charge for polluting while the seller is rewarded for having reduced emissions. Those who can easily reduce emissions most cheaply will do so, achieving pollution reduction at the lowest cost to society.

Emissions trading has another dimension—that of offsetting carbon release by buying credits in activities that absorb or sequester carbon or that replace the use of fossil fuels by energy sources that are carbon free: tree planting or solar, wind, or wave power, for example. By purchasing sufficient credits, the generator of CO₂ can claim to be “carbon neutral.”

Carbon offsetting has its critics. Three of the more telling criticisms are the following:

- It provides an excuse for enterprises to continue to pollute as before by buying credits and passing the cost on to the consumer.
- The scheme achieves its aim only if the mitigating project runs for its planned life, and this is often very long. Trees, for instance, have to grow for 50–80 years to capture the carbon with which they are credited; cut them down sooner, and the offset has not been achieved. Wind turbines and wave power, similarly, achieve their claimed offset only at the end of their design life, typically 25 years.
- It is hard to verify that the credit payments actually reach the mitigating projects for which they were sold: the tree planters or wind turbine builders. Too much of the payment gets absorbed in administrative costs.
- The market has its dark side—insider trading, market fixing—to which the carbon market is as vulnerable as any other.

Newsclip: The great carbon trading scandal.

Distracting local regulators with a fake bomb scare, thieves have made off with 500,000 carbon allowances—intangible products worth around €14 each that are the European Union’s main weapon against climate change.

The Telegraph, January 30, 2011.

5.6 The legislative burden

The burden this legislation places on the materials and manufacturing industries is considerable. The requirements are far-reaching. To recapitulate:

- documentation of the use of any one of 30,000 listed chemicals;
- analysis of energy and material use in all energy-using products;
- finding substitutes for VOCs and other restricted substances;
- mandatory take-back, disassembly, and acceptable disposal of an increasingly large range of products.

Fig. 5.3 summarizes these interventions, suggesting where they influence the flows of the life cycle. The intent of the legislation—that of reducing resource consumption and damaging emissions, and of internalizing the costs these generate—makes sense. The difficulty is that implementing it generates administrative,

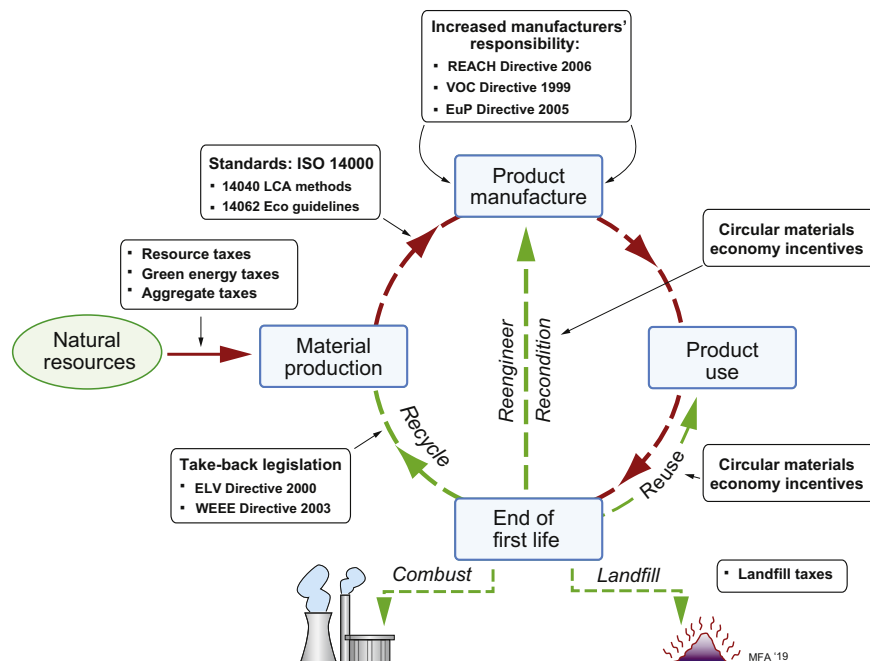


FIGURE 5.3 Interventions and other mechanisms that influence the flows in the material life cycle.

reporting, and other costs in addition to the direct costs of cleanup, thereby adding to the burden on industry.

These additional costs are minimized by the use of well-designed software and other tools. Most of the LCA packages described in the appendix of Chapter 3 were created to help companies analyze their products, using standards that meet the requirements of the legislation. A Web search on any one of the acts and directives listed in Section 5.4 reveals more tools designed to help implement them. The development of tools that integrate with existing PLM (product life-cycle management) systems makes compliance semiautomatic, flagging the use of any material or process that is, in any sense, restricted, and automatically generating the reports that the legislation requires.

5.7 Summary and conclusions

Governments intervene when they wish to change the way people and organizations behave. Many now accept that the way they behave at present is damaging to the environment in ways that could be irreversible. Some of this damage is local and can be tackled at a national level by making the polluter pay or rewarding those that do not pollute. National and multinational regulations, controls, and directives impose

reporting requirements, set tax levels, and establish trading schemes to create incentives for change, with the ultimate aim of making design for the environment a priority.

Some impacts, however, are on a global scale. The externalized costs fall both on the nations responsible for the impact and on those that are not. Solutions here require international agreements. Binding, universal, and enforceable agreements here are out of reach—the diversity of wealth, national priorities, and political systems is too great. Nonetheless, protocols and statements that many nations feel able to sign can be negotiated. It is in furthering these international agreements that we must place our hopes for the future.

But meanwhile, the volume of legislation grows and grows, and with it, the documentation. One only wishes that environmental agencies could aspire to be as concise as Moses.

5.8 Further reading

- Averchenkova, A., Fankhauser, S. and Nachmany, M., Editors, (2017) “Trends in climate change legislation”, Edward Elgar Publishing. (*A collection of essays on the factors that motivate environmental legislation.*)
- Brundtland, G.H. (1987), Chairman, “Our common future” Report of the World Commission on Environment and Development, Oxford University Press, Oxford, UK. (*Known as the Brundtland Report, it defined the principle of sustainability as “Development that meets the needs of today without compromising the ability of future generations to meet their own needs”.*)
- Carson, R. (1962) “Silent Spring”, Houghton Mifflin, republished by Mariner Books, (2002). (*Meticulous examination of the consequences of the use of the pesticide DDT and of the impact of technology on the environment.*)
- ELV (2000) The Directive EC 2000/53 Directive on End-of-life vehicles (ELV) Journal of the European Communities L269, 21/10/2000, pp. 34–42. <http://rod.eionet.europa.eu/instruments/526> (*European Union Directive requiring take back and recycling of vehicles at end of life.*)
- Hardin, G. (1968) “The tragedy of the commons”, *Science*, Vol. 162, pp. 1243–1248. (*An elegantly argued exposition of the tendency to exploit a common good such as a shared resource (the atmosphere) or pollution sink (the Oceans) until the resource becomes depleted or over-polluted.*)
- IPCC (2018) “Special report on global warming of 1.5 °C (SR15)” <https://www.ipcc.ch/> (*A report by the Intergovernmental Panel on Climate Change on the impacts of global warming of 1.5 °C above pre-industrial levels.*)
- ISO 14040 (1998) Environmental management – Life-cycle assessment – Principles and framework.
- ISO 14041 (1998) Goal and scope definition and inventory analysis.
- ISO 14042 (2000) Life-cycle impact assessment.

- ISO 14043 (2000) Life-cycle interpretation, International Organization for Standardization, Geneva, Switzerland. (*The set of standards defining procedures for life cycle assessment and its interpretation.*)
- Meadows D.H., Meadows D.L., Randers J, and Behrens W.W. (1972) "The limits to growth", Universe Books, New York. (*The "Club of Rome" report that triggered the first of a sequence of debates in the 20th century on the ultimate limits imposed by resource depletion.*)
- National Highway Traffic Safety Administration (NHTSA) (2011) "CAFE Overview", https://one.nhtsa.gov/cape_pic/cape_pic_home.htm#:~:text=CAFE%20Overview,of%20cars%20and%20light%20trucks.
- PAS 2050 (2008) "Specification for the assignment of the life-cycle greenhouse gas emissions of goods and services", ICS code 13.020.40, British Standards Institution, London, UK. (*This Publicly Available Specification (PAS) deals with carbon-equivalent emissions over product life.*)
- RoHS (2002), The Directive EC 2002/95/EC on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment. (*This Directive, commonly referred to as the Restriction of Hazardous Substances Directive or RoHS, was adopted by the European Union in February 2003 and came into force on 1 July 2006.*)
- WEEE (2002) The Directive EC 2002/96 on Waste electrical and electronic equipment (WEEE) Journal of the European Communities 37, 13/02/2003 pp. 24–38.

5.9 Exercises

- E5.1.** What is a protocol? What do the Montreal Protocol and the Kyoto Protocol commit the signatories to do? Use the Internet to find out.
- E5.2.** What is meant by "internalized" and "externalized" environmental costs? What legislative steps can be taken to pressure polluters to internalize environmental costs?
- E5.3.** What is the difference between *command and control* methods and the use of *economic instruments* to protect the environment?
- E5.4.** How does emissions trading work?
- E5.5.** Carbon trading and offsetting sound like good ways to reduce emissions, but they have many critics. Use the Internet to research the imperfections in the system and report your findings.
- E5.6.** What are the merits and difficulties associated with (1) taxation and (2) trading schemes as economic instruments to control pollution?
- E5.7.** The fleet average fuel economy of one carmaker fails to meet the present CAFE target (34 mpg) by 3 mpg, incurring a penalty of \$165 per car. Assuming that the first owner of a typical car bought from this carmaker drives it for 100,000 miles before selling it, how much more gasoline will it

burn than a car that meets the standard? If the carbon footprint of gasoline is 2.9 kg/L and 1 US gallon = 3.79 L, how much extra carbon does the car emit? If gasoline costs \$2.54 per US gallon, what is the cost penalty of a deficit of 3 mpg?

E5.8. The CAFE target is raised to 45 mpg. A carmaker with US sales of 500,000 vehicles per year elects to continue to market a range with a fleet fuel average of 35 mpg. What CAFE penalty will the carmaker incur? What is this expressed as a percentage of sales if the carmaker receives 70% of the average showroom price of \$40,000 per car?

E5.9. Your neighbor with a large 4×4 proudly tells you that his car, despite its great size, is carbon neutral. What does he mean (or thinks he means)?

E5.10. In December 2007, Saab posted advertisements urging consumers to “switch to carbon neutral motoring,” claiming that “every Saab is green.” In a press release the company said they planned to plant 17 native trees for each car bought. The company claimed that its purchase of offsets for each car sold made Saab the first car brand to make its entire range carbon free.

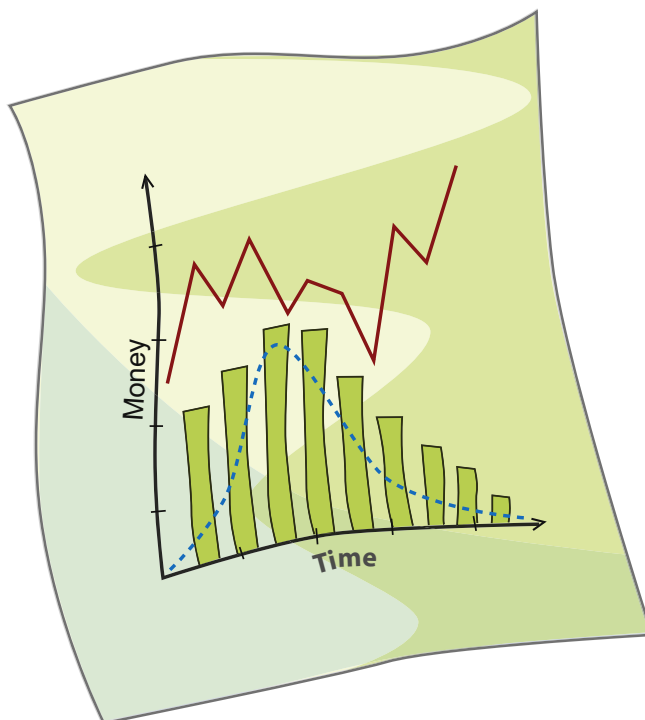
What is misleading about this statement? (The company subsequently withdrew it.)

E5.11. What tools are available to help companies meet the European Union VOC regulations? Use the Internet to find out.

E5.12. What tools are available to help companies meet the European Union EuP (energy-using products) regulations? Use the Internet to find out.

E5.13. What is REACH? What tools are available to implement REACH within a company? Use the Internet to find out.

Eco-data: values, sources, precision



CONTENTS

- 6.1 Introduction and synopsis
- 6.2 Data precision: recalibrating expectations
- 6.3 Eco-properties: materials
- 6.4 Eco-properties: processes
- 6.5 Eco-properties: energy
- 6.6 Eco-properties: transport
- 6.7 Eco-properties: end of life
- 6.8 Summary and conclusions
- 6.9 Further reading
- 6.10 Exercises

6.1 Introduction and synopsis

Decisions need data—that means *numbers*. You can speculate without numbers, but if you want your conclusions to rest on a solid foundation, you need real numbers grounded in evidence. You will find them in Appendixs A and B at the end of this book. Appendix A lists data for the engineering properties of materials. Appendix B does the same for geo-economic and environmental properties. This chapter explains what they mean and how to interpret and use them.

6.2 Data precision: recalibrating expectations

The engineering properties of materials—their mechanical, thermal, and electrical attributes—are well characterized. They are measured with sophisticated equipment following internationally accepted standards and are reported in widely accessible handbooks and databases. They are not *exact*, but their precision—when it matters—is reported; many are known to three-figure accuracy, some to more. A pedigree like this gives confidence. They are data that can be trusted.

Additional properties are needed to incorporate eco-objectives into the design process. They include measures of the energy committed and carbon released into the atmosphere when a material is extracted or synthesized—its *embodied energy* and *carbon footprint*—and similar data for the processing of the material to create a shaped part. There are more, introduced below. But before the introductions, it helps to know what to expect.

Take embodied energy as an example. It is the energy to produce unit mass (usually, 1 kg) of a material from, well, whatever it is made from. It is a key input to any eco-tool. Unlike engineering properties, many with a provenance stretching back 200 years, embodied energy is an upstart, with a brief and not very creditable history. There are no sophisticated test machines to measure it. International standards, detailed in ISO 14040 and discussed in Chapter 3, lay out procedures, but these are vague and not easily applied. So just how far can values for this and other eco-properties be trusted? An analysis, documented in [Section 6.3](#), suggests a standard deviation of *at least* $\pm 10\%$.

Bad news? Not necessarily. It depends on how you plan to use the data. Methods for selecting materials based on environmental criteria must be fit for purpose. The distinctions they reveal and the decisions drawn from them must be *significant*, meaning that they stand despite the imprecision of the data on which they are based.

One way to deal with this is by listing all properties as ranges¹: *aluminum, embodied energy 190–225 MJ/kg*, for example. The ranges allow “best case” and “worst case” scenarios to be explored. When point (single-valued) data are needed, as they are in the examples of this and other chapters, take the mean of the range. Appendix A lists point data for mechanical, thermal, and electrical properties of materials. Appendix B does the same for eco- and supply-chain data.

6.3 Eco-properties: materials

When assessing the eco-impact of a material, there are two considerations: the impact per unit and the number of units produced. [Table 6.1](#) lists geo-economic

¹The database on which much of this chapter is based (CES 2019) stores data in this way.

Table 6.1 Geo-economic and eco-attributes of a material class

Aluminum alloys				
Geo-economic properties				
Global production	37 × 10 ⁶		tonnes/year	
Reserves	2.0 × 10 ⁹		tonnes	
Critical element status: may contain critical elements				
Eco-properties: Material				
Embodied energy, production	190	–	225	MJ/kg
CO ₂ footprint, production	11	–	13	kg/kg
Water usage	495	–	1490	L/kg
Eco-properties: processing				
Casting energy	11	–	12.2	MJ/kg
Casting CO ₂ footprint	0.82	–	0.91	kg/kg
Deformation processing energy	3.3	–	6.8	MJ/kg
Deformation processing CO ₂ footprint	0.19	–	0.23	kg/kg
Recovery at end of life				
Embodied energy, recycling	22	–	39	MJ/kg
CO ₂ footprint, recycling	1.9	–	2.3	kg/kg
Recycle fraction in current supply	41	–	45	%

and eco-properties. Here we explain what the names mean and examine the ranges of their values. The data are drawn from many sources, listed under “Further reading” at the end of this chapter.

Geo-economic properties. The first block of data in Table 6.1 characterizes the resource base from which the material is drawn and the rate at which it is being exploited. The *annual world production* is simply the mass of the material extracted annually from ores or feedstock, expressed in terms of the tonnes of metal (or other engineering material) it yields. The *reserve*, as explained in Chapter 2, is the currently reported size of the economically recoverable ore body from which the material is extracted or created, expressed as the tonnes of metal that it contains.

The elements are distributed across the globe in an uneven way; the richest deposits may lie in the remotest places. Global trade gives nations that lack

them access to supply, supporting world production at a level that meets demand (see Appendix B, Table B1). Events can disrupt the free movement of materials: labor unrest, wars, political intervention, or just plain scarcity. Nations identify materials that are essential for their prosperity and security, classifying them as “critical” if their supply chain is unsure. Materials that contain more than 5% of a critical element are flagged in Appendix B, Tables B2 and B3.

Embodied energy and carbon footprint. The second block of data in Table 6.1 relates to the eco-impact of materials production. *Embodied energy*, H_m , is the energy that must be committed to create 1 kg of usable material—1 kg of steel stock, or of PET (polyethylene terephthalate) pellets, or of cement powder, for example—measured in MJ_{oe}/kg. “MJ_{oe}” means “megajoules, oil equivalent.” Some materials are made using fossil fuel as the primary source of energy; the reduction of iron ore using coke in a blast furnace is an example. Others are made using electrical energy, some proportion of which usually comes from fossil fuels. To allow comparability, the electrical energy has to be corrected back to a fossil fuel equivalent, for which oil is the standard. We won’t write MJ_{oe} all the time, but adopt the convention that chemical energies (like that of oil) are given in MJ and electrical energies in kWh. Their relationship is $1 \text{ kWh} = 3.6 \text{ MJ}_{\text{electrical}} = 3.6/\eta \text{ MJ}_{\text{oe}}$, where η is the conversion efficiency of fossil fuel to electrical energy (typically 38%). Appendix B, Tables B2–B5 list point data for embodied energies for materials.

The *CO₂ footprint* of a material is the mass of CO₂ released into the atmosphere per unit mass of material,² with units kg/kg. CO₂ is a concern because of its global warming potential (GWP), caused by its ability to absorb and trap infrared radiation from the sun. Other emissions, such as carbon monoxide, CO, and methane, CH₄, also have GWP. It is common practice to report what is called the “carbon equivalent,” symbol CO_{2,eq} (units still kg/kg), which is the mass of CO₂ with the same GWP as that of the real emissions. The data for carbon footprint in Appendix B Tables B2–B5 are for CO_{2,eq}.

It is tempting to try to estimate embodied energy via the thermodynamics of the processes involved. Extracting aluminum from its oxide, for instance, requires the provision of the free energy of oxidation of aluminum to liberate it. This much energy must be provided, it is true, but it is only the beginning. The thermodynamic efficiencies of industrial processes are low, seldom reaching 50%. Only part of the output is usable; the scrap fractions range from a few percent to more than 20%. The feedstocks used in the extraction or production themselves carry embodied energy. Transport is involved. The production plant itself has to be lit, heated, and serviced. And if it is a dedicated plant, one that is built for the sole purpose of making the material or product, there is an “energy mortgage”—the energy committed in building the plant in the first place.

²The atomic weight of carbon is 12, that of oxygen is 16, so 1 kg of carbon, when burned, produces $1 + 2 \times 16/12 = 3.7 \text{ kg}$ of CO₂.

Embodied energies are more properly assessed by *resource flow analysis*. For a material such as ingot iron, cement powder, or PET granules, the embodied energy per kilogram is found by monitoring over a fixed period of time the total energy input to the production plant (including that smuggled in, so to speak, as embodied energy of feedstock) and dividing this by the quantity of usable material shipped out of the plant.

The meaning of these quantities is best illustrated by a conducted tour through the life cycle of a single product, taking a PET³ bottle as an example. Fig. 6.1 starts the tour. It shows, much simplified, the inputs to a PET production facility: oil derivatives such as naphtha and other feedstock, direct power (which, if electric, is generated in part from fossil fuels with a conversion efficiency of about 38%), and the energy of transporting the materials to the facility.

The material inputs to any processing operation are referred to as *feedstock*. Some are inorganic, some organic. Accounting for inorganic feedstock is straightforward because, during processing, it appears either in the final product or in the waste output. Accounting for hydrocarbons is more complex because they can be used either as a fuel or as a material feedstock. When a hydrocarbon is burned to provide energy, there is an immediate release of carbon into the atmosphere. When, instead, a hydrocarbon is used as a feedstock (naptha from oil used to make plastics, for example), the energy content is not lost, but is rolled up and incorporated into the product; in that sense it is truly “embodied” in the material. Confusingly, the term “embodied energy” refers not to this, but to all the energy, both fuel and feedstock, associated with material production.

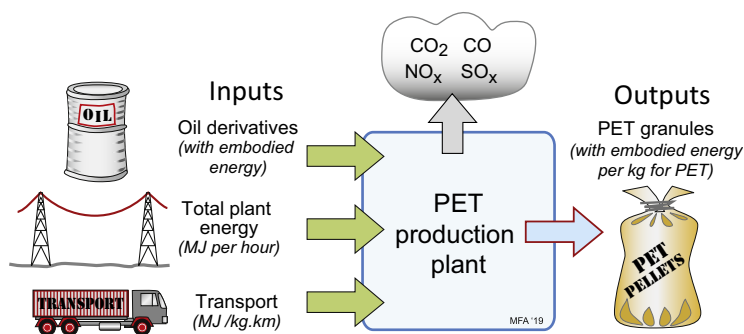


FIGURE 6.1 Embodied energy. Energy enters the plant. Its output is a material. The energy per kilogram of usable material is the embodied energy of the material. PET, polyethylene terephthalate.

³PET is the plastic most widely used for bottled water and soft drinks.

The plant of Fig. 6.1 has an hourly output of usable PET granules. The embodied energy of the PET, $(H_m)_{PET}$, with usual units of MJ/kg, is then given by:

$$(H_m)_{PET} = \frac{\sum \text{Energies entering plant per year}}{\text{Mass of useable PET granules produced per year}} \quad (6.1)$$

The CO₂ footprint of a material is assessed in a similar way. The carbon emissions consequent on the creation of unit mass of material include those associated with transport, the generation of the electric power used by the plant, and hydrocarbon fuels. The CO₂ footprint, with the usual units of kg CO₂/kg, is then the sum of all the contributions, per unit mass of usable material exiting the plant.

Exploring the data: property charts. What does the materials eco-landscape look like? Appendix B Tables B2–B5 give the numbers, useful when you want a value for a specific material, but hopeless for portraying the big picture. We need a drone’s-eye view of what the data look like. The seven data charts in this chapter give this aerial perspective. They are accompanied by commentary on the highs, the lows, the averages, and the exceptions.

Embodied energies per unit mass of materials are compared in Fig. 6.2. The light alloys based on aluminum, magnesium, and titanium (Table B2) have high values, approaching 800 MJ/kg for titanium. Precious metals (Table B3) lie much higher still. Polymers all cluster around 100 MJ/kg, less than the light alloys but considerably more than steels and cast irons, which have energies between 20 and 40 MJ/kg. Technical ceramics such as aluminum nitride have high energies; those for glass, cement, brick, and concrete are much lower. Composites, too, have a wide spread. High-performance composites—here we think of CFRP (carbon-fiber-reinforced polymers)—lie at the top, well above most metals. At the other extreme, paper, plywood, and timber are comparable to the other materials of the construction industry.

Materials differ greatly in density: steel, for example, is almost 10 times denser than polypropylene. That means that comparing materials by energy per unit volume (MJ/m³) gives a different ranking compared with one based on weight (MJ/kg). We’ll see how that plays out in the next couple of paragraphs.

Carbon footprints of materials are compared in Figs. 6.3 and 6.4. The first plots the value per unit mass (per kg) of the material. The pattern is like that of embodied energy: light alloys have a large footprint per kilogram, and steel a low one. Advanced composites (CFRP) are as carbon intensive as titanium. Natural materials, brick, and concrete lie far below them all.

But is carbon *per unit mass* the proper basis of comparison? Suppose, instead, the comparison is made *per unit volume* (Fig. 6.4). The picture changes. Now metals as a family lie above the others, all greater than 10,000 kg/kg. Polymers cluster around 3000 kg/kg; by this measure they are not the carbon-intensive

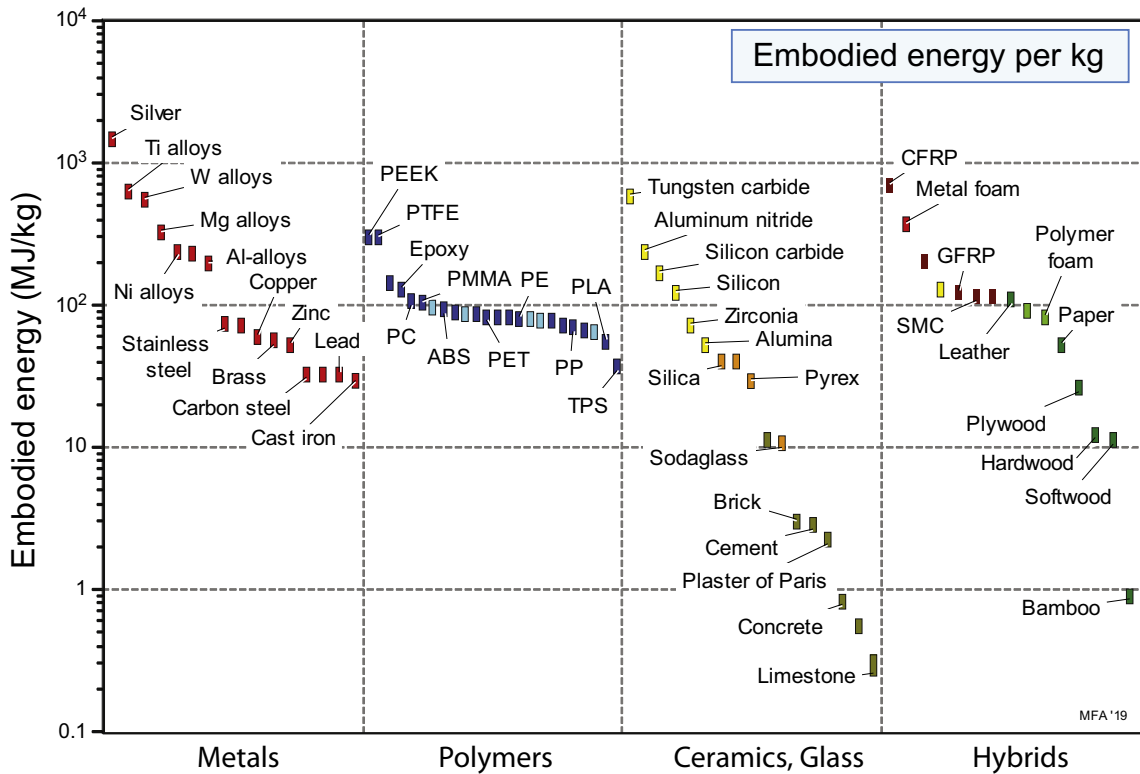


FIGURE 6.2 A bar chart of the embodied energies of materials per unit mass.

materials they are sometimes made out to be. CFRP now lies only a little above aluminum. The materials of construction—brick, wood, concrete—lie far below all of them.

This raises an obvious question: If we are to choose materials with the objective of minimizing their carbon footprint, what basis of comparison should we use? A mistaken choice invalidates the comparison, as we have just seen. The right answer is to compare carbon footprint *per unit of function*. We return to this, in depth, in Chapters 9 and 10.

Carbon-to-energy ratios. Most of the energy used to make materials comes, at present, from fossil fuels. The carbon in those fuels ends up as CO_2 when they are burned to release the energy. You might expect, then, that the two should be proportional.

Fig. 6.5 plots the ratio. Most cluster around $0.06 \text{ kg CO}_2/\text{MJ}$. Magnesium alloys lie higher because the covering gas used to protect the metal during casting contributes to the carbon equivalence but not to the energy. Cement and concrete, too, are high because the calcining of calcium carbonate to make lime releases CO_2 that adds to the CO_2 release from the fuels used in the process. Polymers

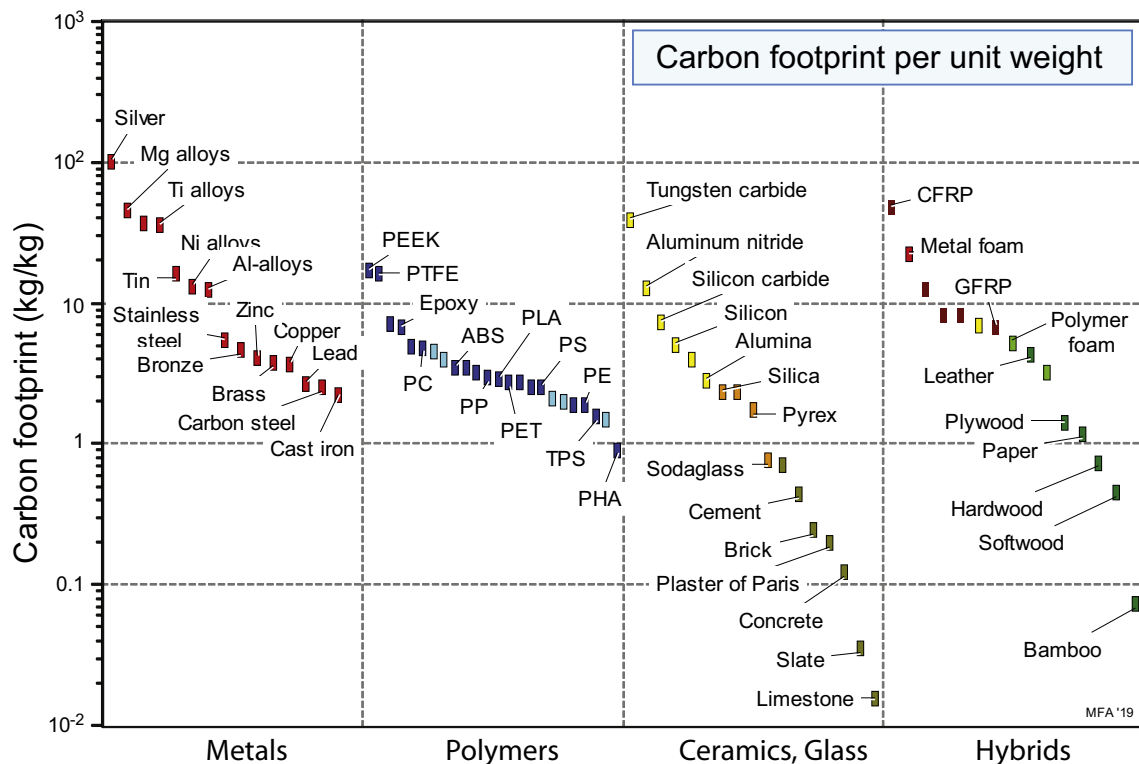


FIGURE 6.3 Annual carbon dioxide per kilogram to atmosphere from material production.

have a low ratio because they use hydrocarbons both as feedstock and as fuel to provide heat; their embodied energy includes both, but their carbon footprint (meaning carbon released to atmosphere) includes only the fuel component. The feedstock component is locked up in the polymer, not released to atmosphere. Natural materials, too, are low because they sequester carbon, reducing the carbon footprint but not the energy used to harvest and treat them.

Total carbon release from material production. Material production pumps enormous quantities of CO₂ into the atmosphere; some 20% of the global total arises in this way. So it is interesting to ask: Which materials contribute the most? That depends on the carbon footprint per kilogram and on the number of kilograms per year that are produced. Fig. 6.6 answers the question and illustrates how the data can be used. It was made by multiplying the annual world production of each material by its carbon footprint to give the tonnage of CO₂ per material per year. The big five are iron and steel, aluminum, concrete (cement), plaster, and paper and cardboard. Between them they account for more than all the rest put together.

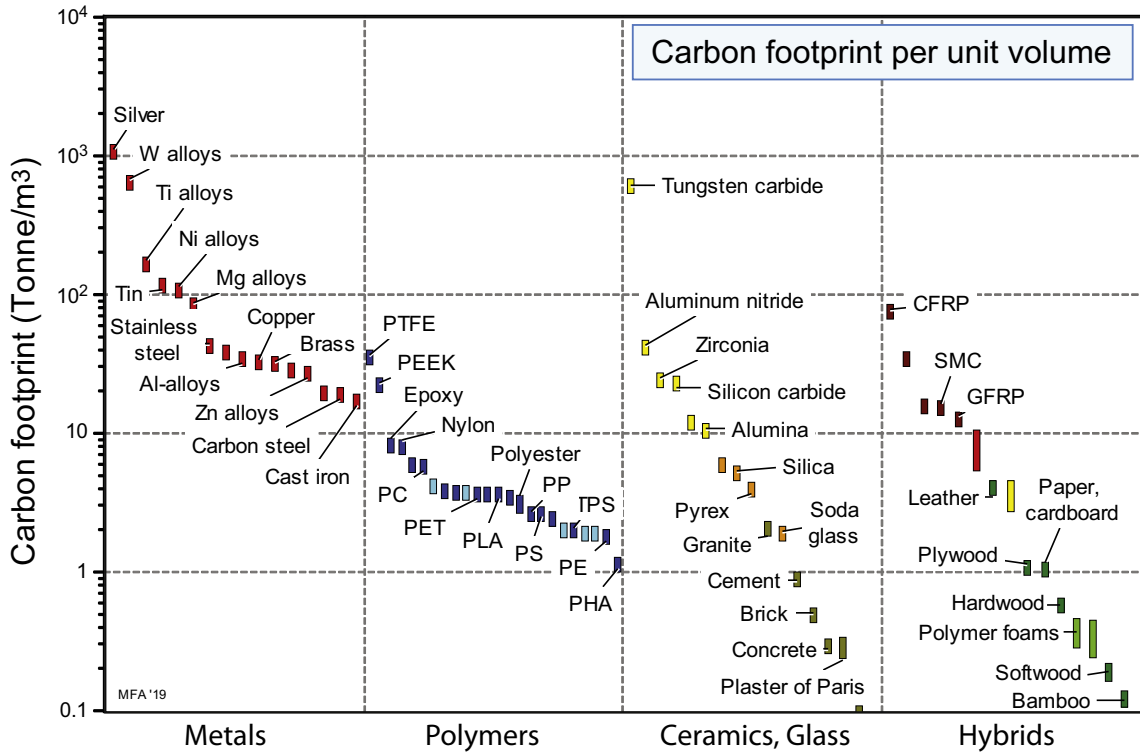


FIGURE 6.4 Annual carbon dioxide per square meter to atmosphere from material production.

Water usage. Making concrete requires water, but not much. Making paper, by contrast, requires so much that papermaking plants, for hundreds of years, have been sited on rivers, which, in the past, they seriously polluted. Fig. 6.7 shows approximate water usage for material production. Broadly speaking, it takes 200 L of water to make 1 kg of plastic, more for metals, less for ceramics and glasses. There is not much else to be said except that the water consumptions plotted here are small compared with those required, per kilogram, for water-intensive agricultural crops like rice (5000 L/kg) and cotton (3000 L/kg), or for materials derived from animal husbandry, like meat, leather, and wool.

Digression: dealing with natural materials. Trees grow by capturing energy from the sun, absorbing CO₂ from the atmosphere, and drawing H₂O from the earth to build hydrocarbons, notably cellulose and lignin. In this way wood “sequesters” carbon, removing it from the atmosphere and storing it. This has led to the statement that the carbon footprint of wood is negative; wood absorbs carbon rather than releasing it.

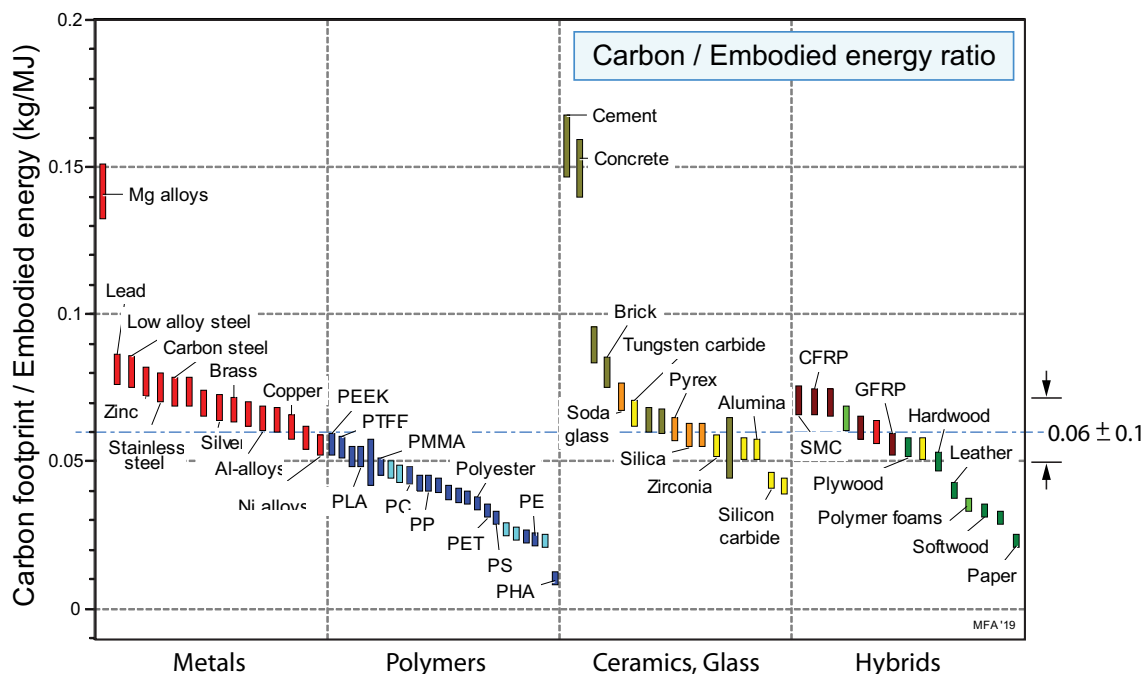


FIGURE 6.5 The ratio of carbon to energy in material production. Most cluster around $0.07 \text{ kg CO}_2/\text{MJ}$. Magnesium alloys, cement, and concrete have high ratios; polymers and natural materials have low.

Many eco-statements need close scrutiny, and this is one. Coal is a hydrocarbon, derived, like wood, from plant life. The carbon in coal was once in the atmosphere; plant life of the carboniferous era captured it and sequestered it as coal. But we do not credit coal with a negative carbon footprint because, when we use it, we do not replace it. The carbon that it sequestered millennia ago is returned to the atmosphere and not recaptured. A carbon credit for wood is only real if the cycle is closed, meaning that the wood is grown as fast as it is used or that it is used for exceedingly long-lived structures, not burned as fuel.

Some plant life, useful in engineering, can be grown “sustainably.” Hemp, used in rope and fabrics, in building construction (as “hempcrete”), and to reinforce polymer composites, is one. Hemp can be grown without fertilizers and it grows fast; it can be grown as fast as it is used. The carbon it sequesters is retained in the fabric, building, or composite made from it, so it genuinely removes carbon from the atmosphere, returning it when it is burned or decomposes at end of life. A carbon-neutral cycle is possible here.

So the question is: Is wood like coal or is it like hemp? At an international level, the world’s forests are being cut down for construction, fuel, pulping, and clearing for agricultural use at a far greater rate than they are replanted. Trees take 80 years to grow to maturity; planting trees to offset the carbon footprint of driving a car

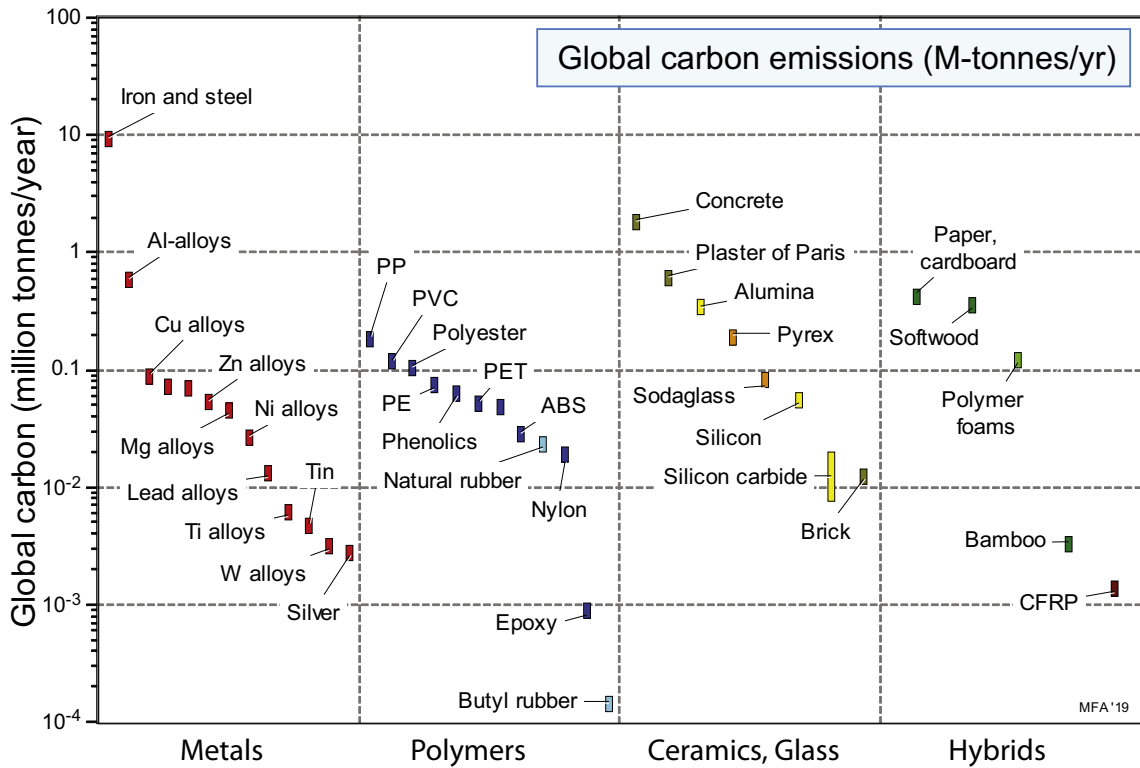


FIGURE 6.6 The global carbon to atmosphere from material production in megatonnes per year.

(average life 14 years) does not add up. Until stocks are replaced as fast as they are used, wood has to be viewed as a resource that is more like coal than hemp, with a corresponding positive carbon footprint.

Today some woods *are* derived from sustainable, managed forests. When woods are known to come from such sources, it is legitimate to credit them with sequestering carbon,⁴ giving them a negative carbon footprint—a point to which we return in Chapter 11.

Wood-based products—plywood, chipboard, fiberboard, and the like—have the merit that they use more of the trunk than paneling or solid wood beams do, and they can be made from lower-grade timber. But all involve a significant component of a polymer adhesive, driving up the energy content and carbon footprint.

Material extraction efficiencies. Using energy to extract and refine materials is an example of an energy-conversion process. Most energy-conversion processes are

⁴Allow for sequestered energy and carbon in woods by subtracting 25 MJ/kg and 2.8 kg CO₂/kg from the values given in the data sheet.

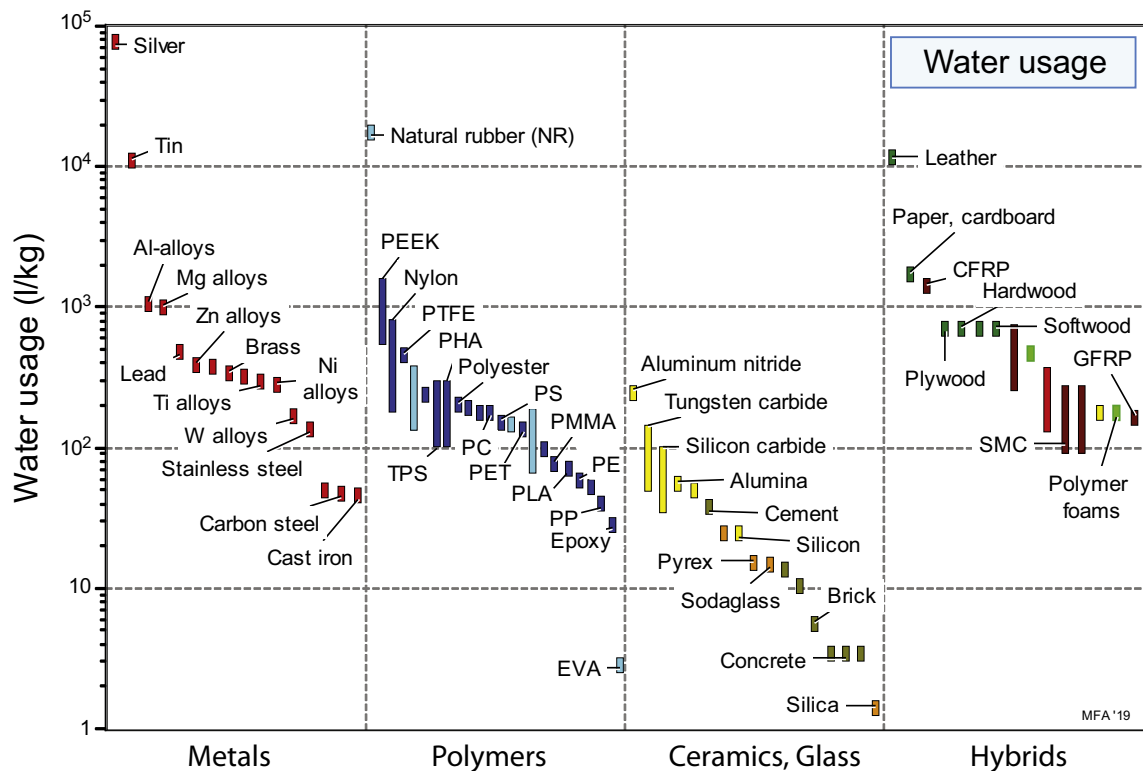


FIGURE 6.7 Water usage in material production (L/kg).

less than 100% efficient, meaning that some energy is “lost” as low-grade heat in the conversion (Appendix B, Table B12). There are many subtleties in defining “efficiency,” η , in a rigorous way. Here we adopt the simple metric:

$$\eta = \frac{\text{Power out}}{\text{Power in}} = \frac{\text{Energy out}}{\text{Energy in}} \quad (6.2)$$

where “power” is energy—in any form—per unit time. Material production efficiencies are low, seldom exceeding 30%, sometimes much less. Here are some examples.

Example: Extraction efficiency of iron

Iron, atomic weight 56 kg/kmol, is made by the reduction of the oxide *hematite*, Fe_2O_3 , in a blast furnace. The free energy of formation of hematite is 826 kJ/mol. What is the minimum energy that must be provided to liberate 1 kg of Fe from Fe_2O_3 ? How does this compare with the reported embodied energy of cast iron, 29 MJ/kg?

Answer. One mole of Fe_2O_3 contains 2 mol of Fe, so a minimum of $826/2 = 413$ kJ liberates 56/1000 kg of iron. Thus the minimum energy to liberate 1 kg of iron from Fe_2O_3 is:

$$H = \frac{413}{56} \times 1000 = 7380 \text{ kJ/kg} = 7.4 \text{ MJ/kg}$$

The reported embodied energy of iron, 29 MJ/kg, is four times larger, giving an apparent conversion efficiency of 25%. Where has the rest gone? Partly as energy dissipated in mining, transporting, and sorting the hematite ore and partly as heat carried away in the gases of the blast furnace. Similar losses reduce the efficiency of all material synthesis and refining.

Example: Efficiency of polymer production

The heat of combustion of polyethylene is 45 MJ/kg. That much energy is truly embodied. But the listed embodied energy of polyethylene is 82 MJ/kg, almost twice as much. The efficiency of polyethylene production is 56%.

Data precision. As eco-studies go, aluminum is among the most explored. Fig. 6.8 plots some of the reported values of its embodied energy over time, starting

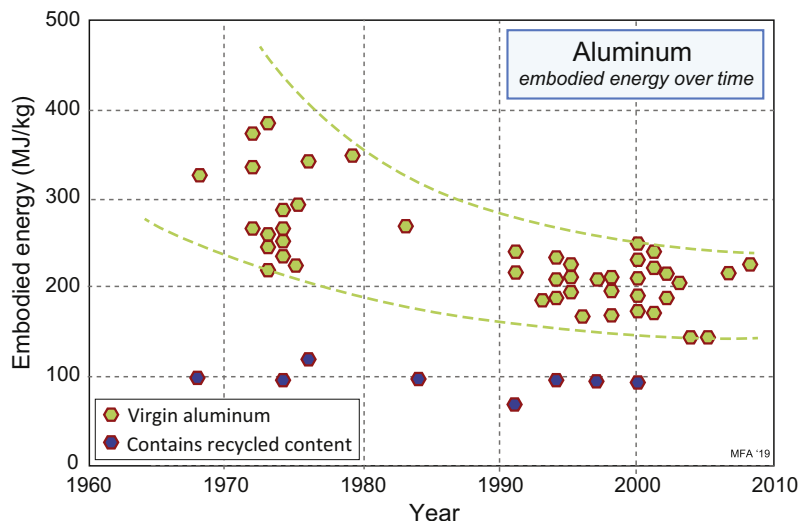


FIGURE 6.8 Data for the embodied energy of aluminum over time, converging on a mean of 190 MJ/kg with a standard deviation of $\pm 17\%$.

with the earliest measurements around 1970. The mean value of the data plotted here converges at the right to a value of 190 MJ/kg; the standard deviation is 17% of the mean. Embodied energies and carbon footprints for other materials show a similar spread. Adding a recycled component reduces the total embodied energy.

Where does this variability come from? The differences in the process routes by which materials are made, the differences in energy mix in electrical power in different countries, and the difficulty in setting system boundaries in assessing energy, CO₂, and the other eco-attributes all contribute to the imprecision. So—bottom line—when dealing with eco-data such as the 190 MJ/kg quoted above, read them thus: the first figure (the 1) can be trusted; the second (the 9) is debatable; the third is meaningless.

Example: using data for carbon footprint

A cooking pot has a cast virgin-aluminum body and a molded phenolic handle. The body weighs 0.8 kg and the handle weighs 0.1 kg. What is the total carbon footprint of the materials of the pot? If the aluminum body were replaced by one made of cast virgin iron weighing three times more, would the total footprint of the pot be less?

Answer. Appendix B2 lists data for the carbon footprint of materials:

Material	Carbon footprint (kg/kg)
Aluminum alloys	12
Cast iron	2.1
Phenolic	1.9

The carbon footprint of the aluminum pot is:

$$0.8 \times 12 + 0.1 \times 1.9 = 9.8 \text{ kg.}$$

That of the cast iron pot is:

$$2.4 \times 2.1 + 0.1 \times 1.9 = 5.2 \text{ kg.}$$

The cast iron pot has a carbon footprint that is 39% less than that of the aluminum one, despite its greater mass. In reality, the aluminum and the cast iron used in an application like this would contain considerable recycled content. This is illustrated in later examples.

Special case (1): precious metals. Precious metals (platinum, gold, silver) are used in small quantities but they carry a heavy burden of embodied energy, carbon, and, of course, cost. Many have unique properties: exceptional electrical conductivity, exceptional resistance to corrosion, and exceptional functional properties as electrodes, sensors, and catalysts. A rule of convenience in energy accounting, used later, is to ignore (or approximate) the contribution of parts of a product

that, collectively, contribute less than 5% to the weight, but we can't do that with precious metals—even a small quantity adds significantly to the energy and carbon totals: 1 g of gold, for instance, has a larger carbon footprint than 10 kg of iron. Table B3 of Appendix B lists the data needed to include them.

Precious metals in engineering structures

A catalytic converter has a steel container weighing 1 kg and an extruded alumina-honeycomb core weighing 0.5 kg coated with 1 g of platinum catalyst. Which of the three components contributes most to the embodied energy of the materials of the converter?

Answer. From Appendix B2 and B3:

Material	Embodied energy (MJ/kg)
Low-carbon steel	31
Alumina	52
Platinum	290,000

The contribution of 1 kg of steel to the embodied energy of the converter is 31 MJ, that of 0.5 kg of alumina ceramic is 26 MJ, and that of 1 g of platinum is 290 MJ. The platinum contributes much more than the sum of the others, despite the tiny quantity.

Special case (2): refractory metals. Electric power generation, flight, and space exploration all depend on alloys that are able to work at high temperatures. Four metals with exceptionally high melting points—molybdenum, niobium, tantalum, and tungsten—are sufficiently important for these technologies that nations stock-pile them and classify them as critical, meaning that they are vital for security and economic growth. They are difficult to extract and carry a high carbon footprint; that of tantalum, for example, is 150 times greater than that of iron. Appendix B, Table B3, lists eco-data for refractory metals. Here is an example of their use.

Example: carbon footprint of superalloys

The cobalt-based superalloy MAR-M 302, used for gas-turbine parts, contains 58% cobalt, 22% chromium, 10% tungsten, and 10% tantalum. What, approximately, is the carbon footprint of MAR-M 302?

Answer. Data for the CO₂ footprints of the components, from Appendix B3, are listed below, with the contribution that each makes to that of MAR-M 302. Its carbon footprint is approximately 39 kg/kg. The contribution from Ta exceeds all the others.

Material	Composition (wt%)	Carbon footprint of element (kg/kg)	Contribution to MAR-M 302 (kg/kg)
Cobalt	58	8.3	4.8
Chromium	22	21	4.6
Tungsten	10	35	3.5
Tantalum	10	260	26
		Total	39

Special case (3): electronics. Electronic components—integrated circuits, surface-mount devices, displays, batteries, and the like—are now an integral part of most appliances. They don’t weigh much, but they are energy and carbon intensive to make. The process routes by which they are made are so complex that calculating the embodied energy from the composition alone is not possible. Table B4 of Appendix B assembles data derived from life-cycle analyses of electronic systems, subsystems, and components. The precision is low, but they give an indication of their relative contributions.

What do the data say? Principally that electronics have embodied energies and carbon footprints that are larger, by a factor of 10–50, than those we associate with conventional engineering materials.

Example: energy and carbon footprint of electronics

A fire-alarm has two AA Ni–Cd batteries, small-device electronics weighing 30 g, and a phenolic casing weighing 200 g. Which of these makes the largest contribution to the embodied energy and carbon footprint of the product?

Answer. From Appendix B2 and B4 we have:

Component and material	Embodied energy	Carbon footprint
Ni–Cd AA battery	3 MJ/unit	0.2 kg/unit
System, small electronic device	2800 MJ/kg	210 kg/kg
Phenolic	77 MJ/kg	1.9 kg/kg

Thus the embodied energy of the device is:

$$H = 2 \times 3 + 0.03 \times 2800 + 0.4 \times 77 = 121\text{MJ}.$$

Its carbon footprint is:

$$\text{CO}_2 = 2 \times 0.2 + 0.03 \times 210 + 0.4 \times 1.9 = 7.5\text{kg}.$$

The electronics account for less than 10% of the weight of the device, but 70% of its energy and carbon footprints.

Special case (4): materials of architecture and construction. Construction of domestic and commercial buildings consumes materials on an enormous scale. The structure uses the most; the envelope enclosing and insulating the structure comes second, the services are third, and the interior finishing and decoration require the least, but all are large. The materials of construction are a little more specialized than those of general engineering; many are not really “materials” but are “systems.” They are assembled with their embodied energies and carbon footprints in Appendix B5 under the subheadings Primary structure, Enclosure, Services, and Interior.

Example: carbon footprint of structure and enclosure

The structure of a steel-framed building requires, per square meter of floor area, 625 kg of standard concrete (foundation) and 86 kg of steel (100% recycled). The enclosure, per square meter of floor, requires 0.2 m³ of fiberglass insulation and 6.6 m² of ¾-inch (19 mm) plywood. What, approximately, is the carbon footprint of structure plus enclosure per square meter?

Answer. Drawing data from Appendix B5 for the carbon footprint:

Component	Carbon footprint	Quantity	Contribution, kg/m ²
Concrete, standard	0.1 kg/kg	625 kg	62.5
Steel, 100% recycled	0.57 kg/kg	86 kg	49
Fiberglass insulation	67 kg/m ³	0.2 m ³	13.4
Plywood	480 kg/m ³	$6.6 \times 0.019 = 0.125 \text{ m}^3$	60
	Total		185

The carbon footprint of the structure plus enclosure is 185 kg/m².

6.4 Eco-properties: processes

Back now to the tour of the PET bottle-making plant. The PET pellets of Fig. 6.1 become the input to a facility for blow-molding PET bottles (Fig. 6.9). The molding operation consumes energy and feedstock. Emissions and waste are excreted. The products—PET blow-molded bottles—emerge.

Primary processing: energy and CO₂ footprint. Blow-molding is a *material-shaping process*. Shaping processes use energy and they have an associated carbon footprint. The processing energy H_p is the energy in MJ/kg required to shape a material. Metals, typically, are cast, rolled, or forged. Polymers are molded or extruded. Ceramics are shaped by powder methods, composites are created by molding or lay-up techniques. The energy consumed by a casting furnace or an injection molding machine can be measured directly, but the production plant as

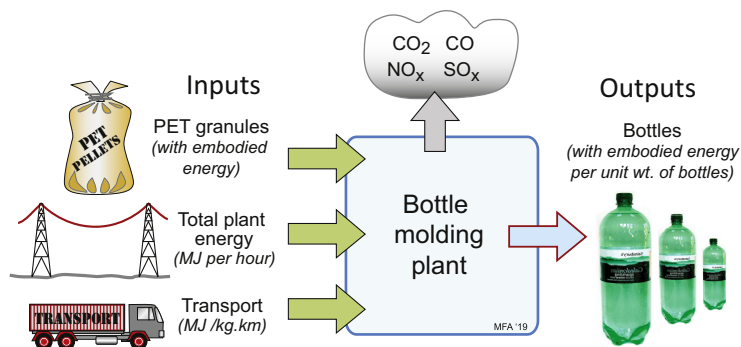


FIGURE 6.9 The shaping of polyethylene terephthalate (PET) to make bottles. Energy is involved, and there is a carbon penalty.

a whole uses more energy than this through the provision of transport, heating, lighting, management, and maintenance. A more realistic measure of processing energy is the total energy entering the manufacturing plant (but excluding that embodied in the materials themselves, since that is attributed to the material-production phase of life) divided by the weight of usable shaped parts that it delivers, giving a value in MJ/kg. The CO₂ footprint is evaluated by direct measurement or by calculating it from the energy use and fuel type. Appendix B6 lists approximate values for both.

Shaping-process energies are plotted in the upper part of Fig. 6.10. The efficiencies of these processes are low, meaning that they use many times more energy than the ideal minimum. The “ideal” energy for casting is that needed to raise the metal to its melting point plus that required to melt it (the latent heat of melting). In practice, casting energies are five or more times greater than this. Why? The metal is held in a crucible and it, too, has a heat capacity. There are heat losses by conduction, convection, and radiation. If the heat source is fossil fuel-generated electricity, there is another multiplier of 3 to allow for conversion efficiency at the power-station. There is the energy to make and bake the molds, to trim the castings, and to account for metal “losses” as cutoffs and imperfect castings. Other shaping processes have similar low efficiencies. Carbon footprints follow a similar pattern.⁵

Secondary processes take a shaped part and add features, or join or finish it. There are many such processes. The energy demands and CO₂ emissions of a basic subset are assembled, as typical ranges, in Appendix B6. They have different units: MJ and kg carbon *per kilogram of material removed for machining*; MJ and kg carbon *per square meter* for painting, plating, and adhesives; and MJ and kg carbon

⁵Carbon footprint can be estimated from process CO₂ (kg/kg) = 0.065 × process energy (MJ/kg).

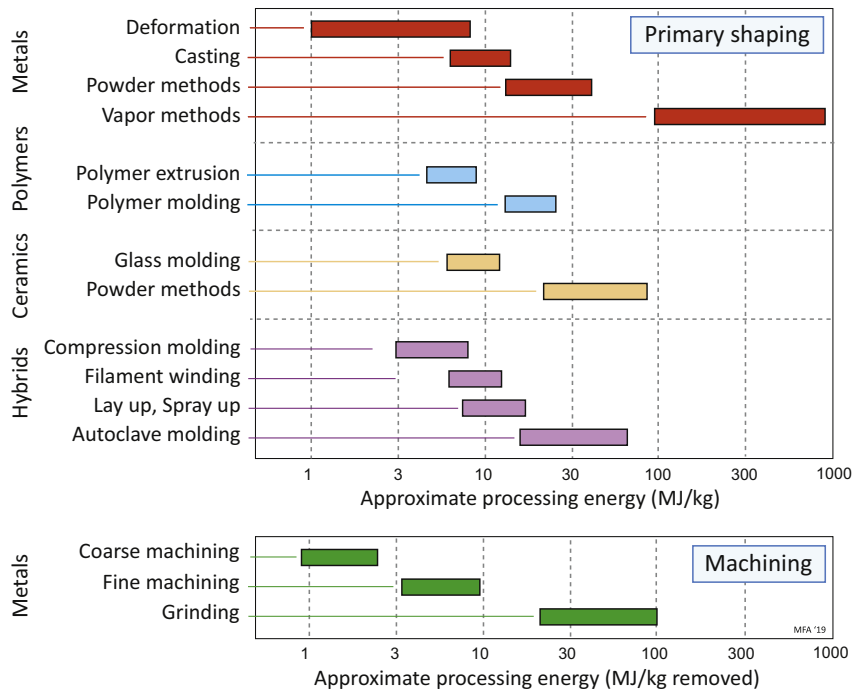


FIGURE 6.10 Approximate processing energies for materials.

per meter for welding and riveting. Machining-process energies appear in the lower part of Fig. 6.10.

What does this figure tell us? That the energy and carbon footprint of an individual process is a lot less than those associated with making the materials in the first place. But processing often involves a chain of shaping, joining, and finishing steps. The sum of these steps, in terms of energy, carbon, and cost, can be comparable to the embodied energy of the material itself.

Example: efficiency of shaping processes

Casting requires that a metal be heated from room temperature T_o to its melting point T_m , requiring $(T_m - T_o)C_p$, where C_p is the specific heat, and then melted, requiring the latent heat of melting, L_m . Copper has the following thermal properties: melting point 1080°C , specific heat $380 \text{ J/kg}\cdot^\circ\text{C}$, latent heat of fusion 13 kJ/mol , and atomic weight 64 kg/kmol . How does the minimum energy required to melt copper compare with the listed energy of casting for copper of 9 MJ/kg ?

Answer. The minimum energy to melt copper is $(T_m - T_o)C_p + L_m$.

Using the data given in the example,

$$(T_m - T_0) \cdot C_p = \frac{1080 \times 380}{1 \times 10^6} = 0.14 \text{ MJ/kg}$$

and $L_m = \frac{13}{1 \times 10^3 \times 0.064} = 0.20 \text{ MJ/kg}$

giving a total of 0.34 MJ/kg. Based on the listed energy of casting of 9 MJ/kg, the efficiency of casting is about 4%.

Example: process chains

Many processes involve chains of energy-conversion steps. Fig. 2.7 showed one. Oil (the primary energy) is drawn from a well. It is processed into a usable form with a loss of 3%. The fuel oil is converted to electrical energy with a conversion efficiency of 38%. The electrical energy is transmitted to the point of use with transmission losses of 10%, where a motor converts it to mechanical energy with an efficiency of 85%. The motor drives a hydraulic pump with losses of 10%, which in turn powers a stamping press, which converts hydraulic pressure into kinetic energy with an efficiency, allowing for standby losses, of 35%. What is the overall conversion efficiency of the chain of Fig. 2.7?

Answer. The overall efficiency $\eta_{tot} = 0.97 \times 0.38 \times 0.9 \times 0.85 \times 0.9 \times 0.35 = 0.1$. Ninety percent of the primary energy is lost as low-grade heat.

Example: the relative magnitudes of energies of material and processing

Flat, rolled mild steel panels, 0.5 m × 0.5 m × 1 mm, are required for cladding. The density of steel is 7900 kg·m³. The panels have a baked-on coating on one surface only. Compare the energies associated with material production, primary shaping, rolling, and the coating for the panel, using data from Appendix B, Tables B2 and B6.

Answer. One panel has a coated surface area of 0.25m² and weighs 2 kg. Drawing data from Appendix B and taking the means of the ranges, we find:

Material and process step: mild steel panel	Energy	Unit
Embodied energy (Table B2)	31	MJ/kg
Deformation processing energy (Table B6)	4.5	MJ/kg
Energy for a baked coating (Table B6)	65	MJ/m ²

The embodied energy of the material of the panel is:

$$2 \times 31 = 62 \text{ MJ.}$$

The primary deformation processing of the panel is:

$$2 \times 4.5 = 9.0 \text{ MJ.}$$

The energy required to bake-coat the panel is:

$$0.25 \times 65 = 16 \text{ MJ.}$$

The largest contribution is that of the embodied energy of the steel. The total processing energy is less than half that of the embodied energy of the material.

6.5 Eco-properties: energy

It might seem that a PET water bottle would not require energy or cause carbon emissions during its life, but that is wrong. The bottles are transported to the filling plant, filled, distributed (sometimes over large distances), and refrigerated before finally being consumed (Fig. 6.11). Every step involves energy and energy means carbon.

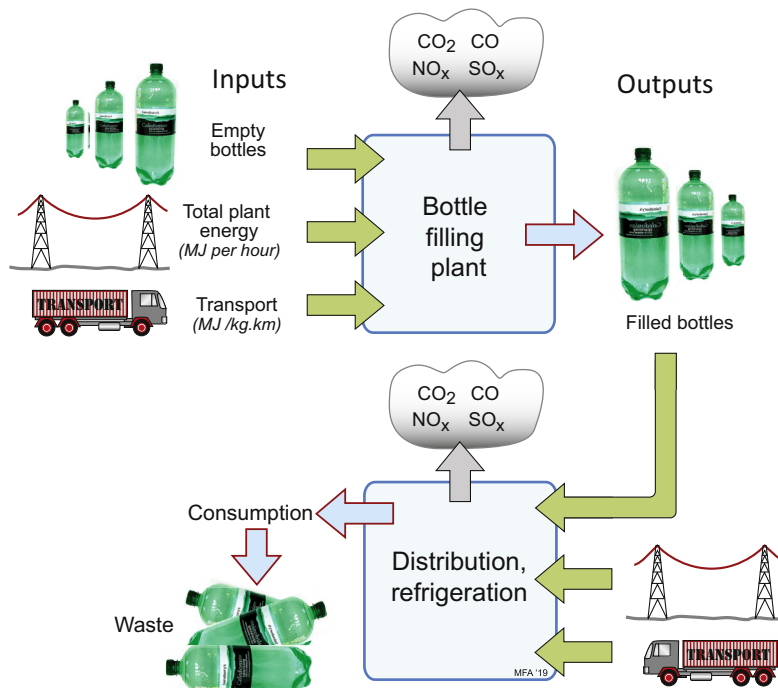


FIGURE 6.11 The use phase of polyethylene terephthalate water bottles: filling, distribution, and refrigeration. Energy is consumed in transport and refrigeration.

More generally, energy is used to transport materials and products from where they are made to where they are used. The products themselves use energy during their life; some use a great deal. This energy is provided predominantly by fossil fuels (oil, gas, coal) and by electric power from a mix of sources. These energy sources differ in their energy intensity and carbon release.

Energy intensities of fossil fuels and their carbon footprints are listed in Table 6.2 (a fuller table appears in Appendix B, Table B9). Reading across, there is the fuel type, the oil equivalent (OE: the kg of crude oil with the same energy content as 1 kg of the fuel), the energy content, and the CO₂ release per unit liter, per kilogram, and per megajoule.⁶

The oil and carbon equivalence of electric power. Electricity is the most convenient form of energy. Today most is generated by burning fossil fuels. Supply constraints and environmental concerns motivate governments to switch to nuclear and renewable sources. The *energy mix* in the electricity supply of a country is the proportional contribution of each source to the total. They differ widely (Appendix B, Table B11). Australia relies heavily on fossil fuels for almost all its electricity, as do China and India. In France the source is predominantly nuclear. Norway relies almost entirely on hydroelectric power. Iceland depends solely on geothermal heat.

Use-phase energy and carbon footprint. Many products consume energy, or energy is consumed on their behalf, during the use phase of life. As we shall see in Chapter 7, this use-phase energy is often larger than that of any other phase. When fossil fuels are used directly (as in the use of gasoline to power cars), the primary energy and CO₂ can be read directly from Appendix B, Table B9. When instead it is used as electricity, the relevant fossil fuel energy and CO₂ depend on the energy mix and generation efficiency, and these differ from country to country. It is then necessary to convert the electrical energy, usually given in

Table 6.2 The energy intensity of fuels and their carbon footprints						
Fuel type	Kg OE ^a	MJ/L	MJ/kg	CO ₂ , kg/L	CO ₂ , kg/kg	CO ₂ , kg/MJ
Coal (average)	0.68	—	26	—	2.3	0.084
Crude oil	1.0	38	44	3.1	3.0	0.070
Diesel	1.0	38	44	3.1	3.2	0.071
Gasoline	1.05	35	45	2.9	2.89	0.065

^aKilograms oil equivalent (the kg of oil with the same energy content).

⁶SI units (kg, MJ, etc.) are used here. Conversion factors to other systems (lb, Btu, etc.) can be found at the end of the book.

kWh, to MJ and CO₂ oil equivalent by multiplying by the conversion factors in the last two columns of Table 6.2 or its expanded version, Table B10.

Example: use-phase energy and carbon

A commercial clothes dryer is rated at 10 kW. It has an anticipated duty cycle averaging 30 hours per week over its design life of 5 years. It is installed in a state in which 80% of the electrical power is derived from oil-fired power stations with a conversion efficiency of 36%; the rest is from renewables. What is the expected life use energy and carbon footprint of the dryer?

Answer. The energy used over life is:

$$(10 \times 30 \times 52 \times 5) = 78,000 \text{ kWhr of electric power.}$$

A fraction, 0.8, of this energy, 62,400 kWhr, is derived from oil. Multiplying this by 3.6 to convert to MJ_{electric} and then dividing by the conversion efficiency 0.36 gives the oil-equivalent energy:

$$62,400 \times 3.6/0.36 = 624,000 \text{ MJ}_{\text{oe}}.$$

Multiplying this by the carbon/MJ of crude oil, 0.07 kg_{CO2}/MJ, from Table 6.2 gives the life carbon footprint of the dryer:

$$624,000 \times 0.07 = 43,680 \text{ kg of CO}_2.$$

In summary, the dryer consumes 78 GWhr of energy and is responsible for just under 44 tonnes of carbon emission.

6.6 Eco-properties: transport

Manufacturing is now globalized. Products are made where it is cheapest to make them and then transported, frequently over large distances, to the point of sale. The energy and carbon associated with transport are most conveniently expressed as the *energy consumed per tonne per kilometer* (MJ/tonne·km), carrying with it an associated *CO₂ footprint* (kg/tonne·km). People, too, are transported, locally by train, bus, or car, further afield by ship or plane. Travel has its own energy demands (MJ/passenger·km) and carbon footprint (CO₂/passenger·km).

Reported data for transport energy and carbon footprint vary considerably. This is partly because the efficiency of transport systems varies from country to country and partly because of a lack of agreement on what should be included. Should the assessment be based on the fuel consumption alone or should the contributions of the roads, rail, or other infrastructure be included? The second estimate gives values that are roughly twice as large as the first. Including infrastructure creates a system boundary problem—do you also include the energy to make the

equipment that built the roads? Here we adopt the simpler, lower estimate based on fuel (and other direct consumables) alone. Appendix B, Table B9 lists transport energies and carbon footprints for freight and personal transport.

Fig. 6.12 shows what they look like. Values for a given journey are calculated by multiplying the weight of the product or number of people by the distance traveled and the fuel–vehicle coefficients listed in the table. A five-seat family car weighing 1400 kg requires about 0.6 MJ/passenger·km. Intercity trains consume 0.09–0.23 MJ/seat·km, with high-speed trains (300 km/hr or more) at the upper end of this range. Aircraft consume between 1.8 and 4.5 MJ/seat·km.

Using transport data

Cars manufactured in China are shipped 19,000 km to Europe by VLC (very large container ship) where they are transported 500 km by 55-tonne truck to the point of sale. If the car weighs 1400 kg, how much energy is used in this transport cycle? If both the VLC and the truck are diesel powered, what are the carbon emissions associated with transporting one car?

Answer. From Table B9 the energy required for ocean shipping is 0.04 MJ/tonne·km and that for 55-tonne truck is 0.71 MJ/tonne·km. Thus the energy of the transport cycle is:

$$1.4(19,000 \times 0.04 + 500 \times 0.71) = 1135 \text{ MJ.}$$

Table B9 gives the carbon intensity of diesel fuel as 0.071 kg/MJ, so transporting one car results in the emission of 80.5 kg of CO₂.

Special topic: energy, carbon, and cars. The fuel consumption and CO₂ emission of cars increase with their weight. Figs. 6.13 and 6.14 show the evidence. The first is a plot of fuel consumption per kilometer, H_{km} (MJ/km), against mass on log scales, allowing a power-law fit. The data suggest the relationship:

$$H_{km} \approx C_{km} m^{0.93} \tag{6.3}$$

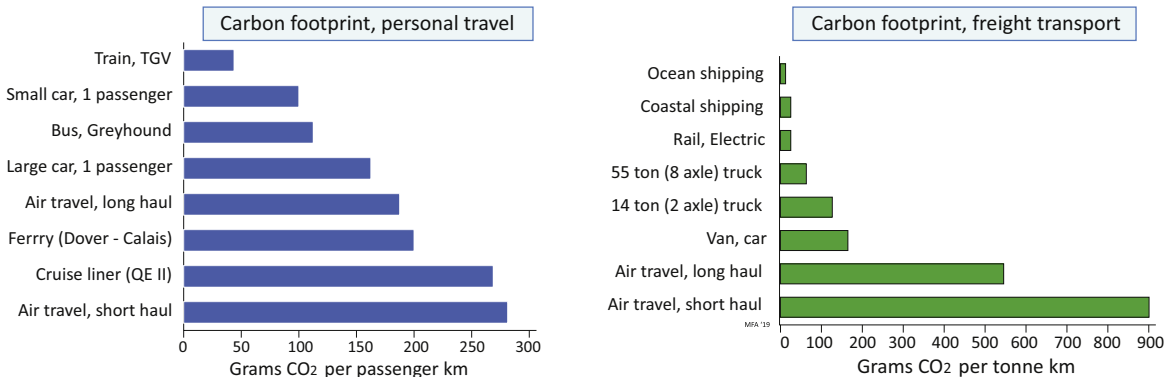


FIGURE 6.12 The carbon footprint of personal travel and freight transport.

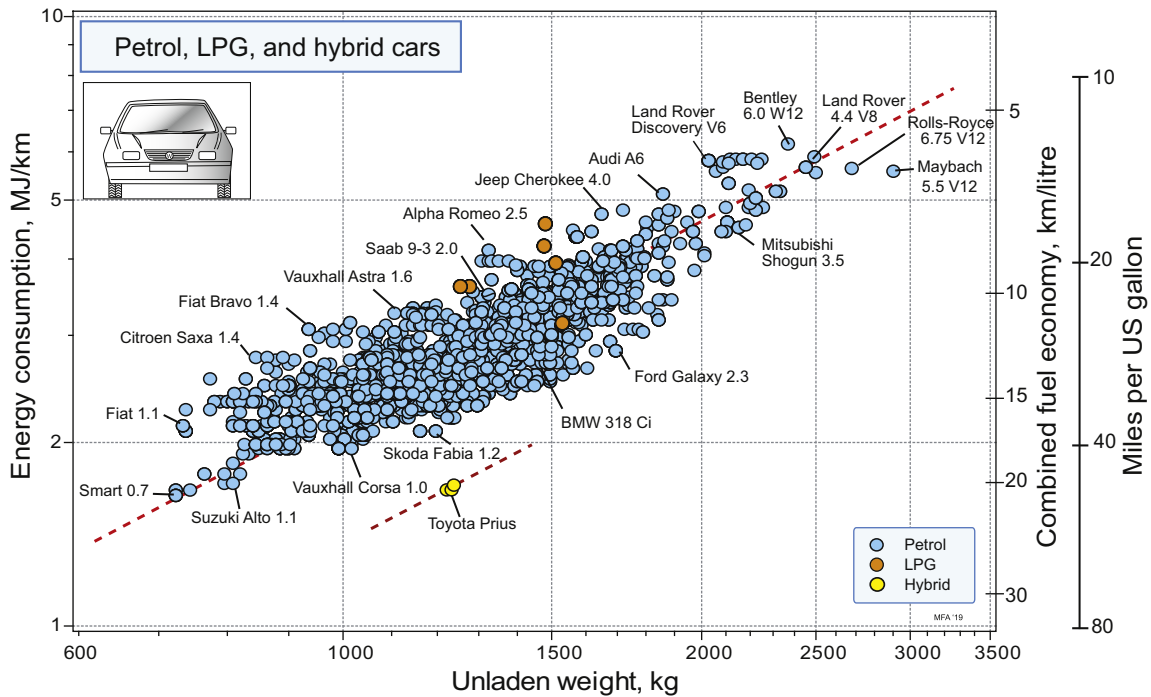


FIGURE 6.13 Energy consumption of petrol, liquefied petroleum gas (LPG), and hybrid engine cars as a function of weight.

Values for the constant C_{km} are listed in Table 6.3.

The second, Fig. 6.14, shows the carbon rating in g/km as a function of energy per kilometer (MJ/km) on linear scales. The two are proportional, with the constants of proportionality marked on the figure.

The energy penalty associated with 1 kg of increased weight is found by differentiating the expressions for H_{km} . The results for a car of weight 1000 kg are listed in the last column of the table. We now have the inputs we need for modeling and selection.

Example: saving energy by reducing weight

An individual uses a small petrol-powered car to commute to work. The car weighs 1000 kg. The rear seating weighs 25 kg. How much energy and carbon would be saved over a duty life of 150,000 km by taking the rear seating out?

Answer. The use energy per unit mass of a petrol-powered 1000 kg car, from Table 6.3, is 0.0021 MJ/km • kg. Thus, reducing the mass by 25 kg will, over 150,000 km, reduce the energy the car requires by:

$$0.0021 \times 25 \times 150,000 = 7875 \text{ MJ.}$$

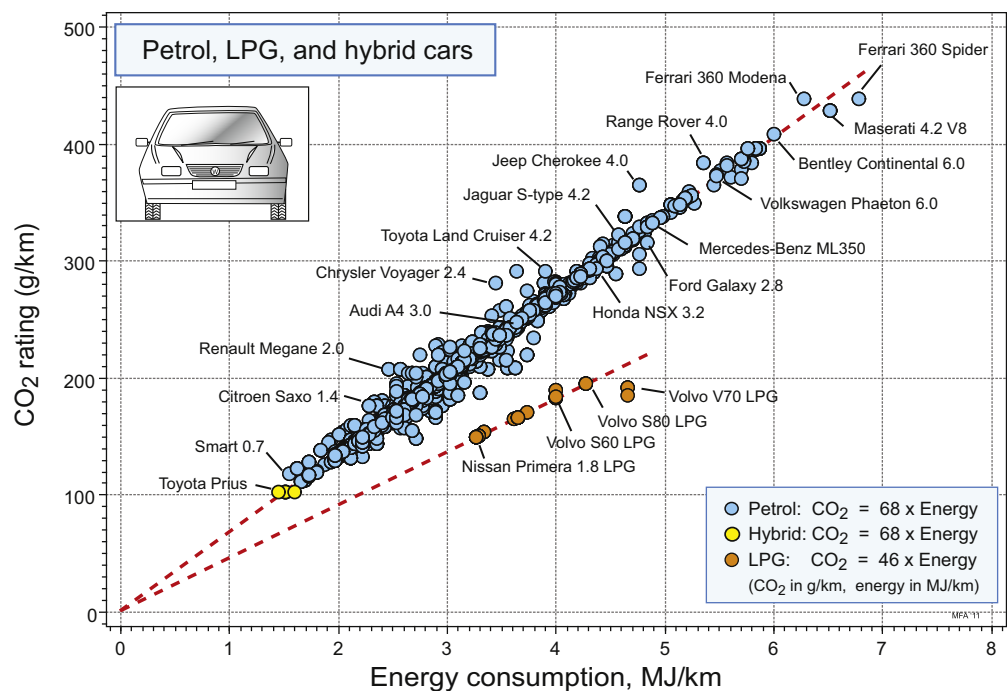


FIGURE 6.14 CO₂ emission of petrol, liquefied petroleum gas (LPG), and hybrid engine cars.

Table 6.3 The energy intensity of cars

Fuel type	C_{km} (for m in kg and H_{km} in MJ/km)	$\frac{CO_2/km}{MJ/km}$ (in grams/km in MJ/km)	$\frac{dH_{km}}{dm}$ (MJ/km · kg) for $m = 1000$ kg
Petrol power	3.7×10^{-3}	68	2.1×10^{-3}
Diesel power	2.8×10^{-3}	76	1.6×10^{-3}
LPG power	3.8×10^{-3}	46	2.2×10^{-3}
Hybrid power	2.3×10^{-3}	68	1.3×10^{-3}

LPG, liquefied petroleum gas.

Table B10 of Appendix B gives the carbon per unit energy of gasoline as 0.065 kg/MJ. Thus, the reduced mass will reduce carbon emission over life by:

$$0.065 \times 7875 = 512 \text{ kg.}$$

In summary, removing the seating can save 7.8 GJ of energy and just over half a tonne of carbon.

Data life. If an aircraft, designed and built 25 years ago, requires replacement parts, they have to be made of the same alloy that was used when the plane was first built—a change can invalidate the airworthiness certificate. When a nuclear reactor is decommissioned, the chemical composition of its materials determines the life and intensity of fission products that have to be contained. These are just two examples of the importance of curating data. It is not a short-term problem. Boeing keep records of all materials used in their planes for 60 years. Nuclear safety inspectorates, when asked about data life, say “infinite.” Emerging standards ISO 14721 (2003) and ISO 10303 parts 45 and 235 relate to the safe long-term storage of material property data.

Newsclip: Concrete is remixed with environment in mind

Portland cement has been around since the early 1800s..... Aesthetic considerations aside, concrete is environmentally ugly. The manufacturing of Portland cement is responsible for about 5 percent of human-caused emissions of the greenhouse gas carbon dioxide. ‘The new twist over the last 10 years has been to try to avoid materials that generate CO₂’ said Kevin A. MacDonald, vice president for engineering services of the Cemstone Products Company. In his mixes, Dr. MacDonald replaced much of the Portland cement with two industrial waste products—fly ash, left over from burning coal in power plants, and blast-furnace slag. Both are what are called pozzolanas, reactive materials that help make the concrete stronger. Because the CO₂ emissions associated with them are accounted for in electricity generation and steel making, they also help reduce the concrete’s carbon footprint.

The New York Times, March 31, 2009.

6.7 Eco-properties: end of life

On with the tour of life as a PET bottle, now at the end of its useful life (Fig. 6.15). Here we jump to the last block of attributes listed in Table 6.1: those relating to *recycling*.

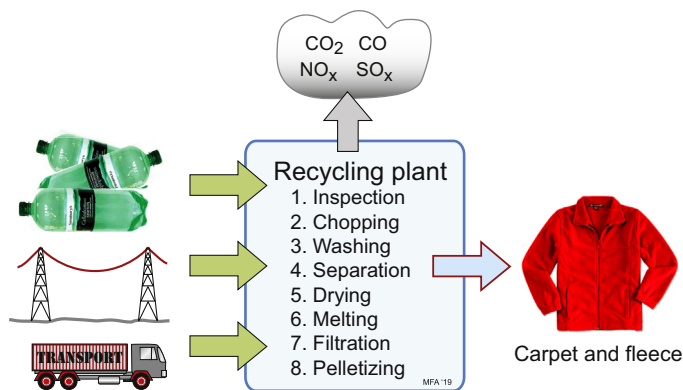


FIGURE 6.15 *Recycling. Many steps are involved, all of which consume some energy, but the embodied energy of the material is conserved.*

Recycling and end of life.⁷ Not all the embodied energy of a material is really “embodied,” but some is. This retained energy means that the energy to recycle a material is usually less than that required for its first production. The recycled fraction in current supply (Appendix B, Table B7, and Fig. 6.16) is an indicator of the viability of recycling. Typical values for metals lie in the range 30%–60%. Glass (22%) and paper (71%), too, are recycled extensively, but polymers are not: only PET is recycled to any large degree. This is because metals are easy to identify and to separate, and because the energy needed to recycle them, typically, is about one-fifth of that required to make them in the first place.

Polymers are more difficult to identify automatically, the energy savings offered by recycling is smaller, and the number of steps involved is large (they are listed on Fig. 6.15). The commodity polymers are used in large quantities, many in products with short life, and they present major problems in waste management, all of which, you would think, would encourage effective recycling. But the economics of polymer recycling are unattractive, with the result that the contribution to current supply for most of them is small.

Example: using data for carbon footprint

A cooking pot—the subject of an earlier example—has a cast aluminum body and a molded phenolic handle. The aluminum has a typical (43%) recycled content. The body weighs 0.8 kg and the handle weighs 0.1 kg. What is the total carbon footprint

⁷Many products are shredded before sorting and separation at end of life. The energy for shredding is approximately 0.1 MJ/kg.

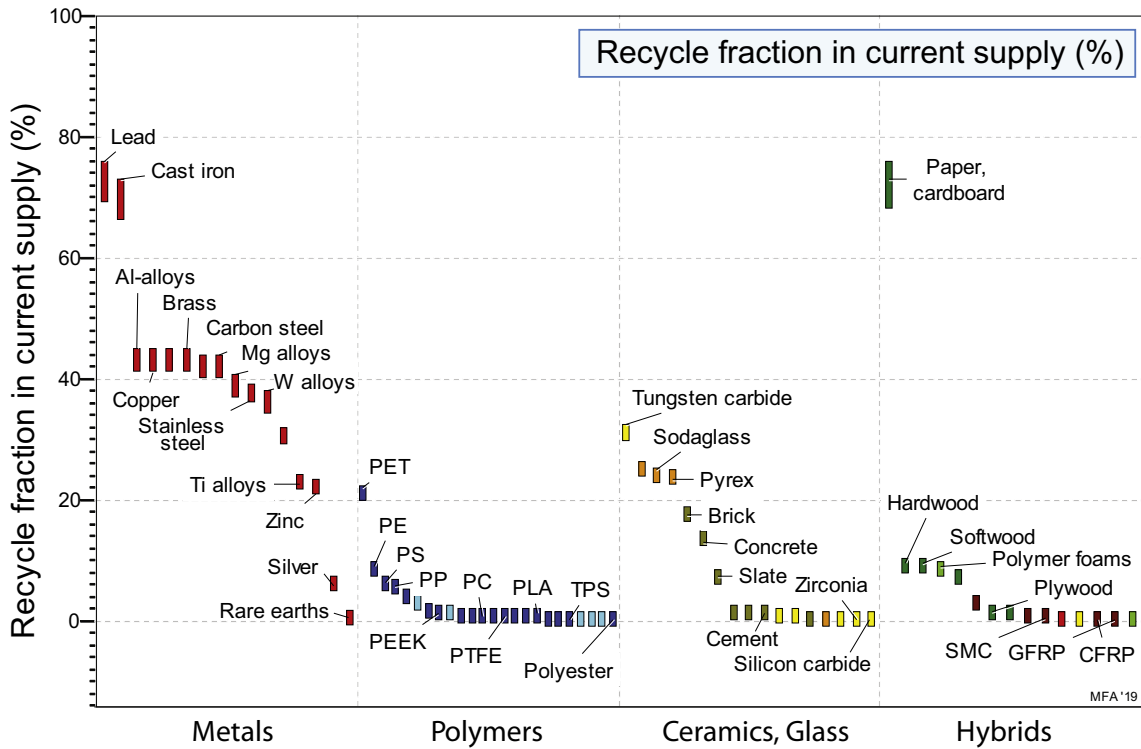


FIGURE 6.16 Recycle fraction in current supply. Metals are extensively recycled. Most other materials are not.

of the materials of the pot? If the aluminum body were replaced by one made of cast iron with typical (67%) recycled content, weighing three times more, would the total footprint of the pot be less?

Answer. Appendix B, Table B2 lists data for the carbon footprint of virgin materials. Table B7 does the same for recycled materials. The carbon footprint of the materials with the stated recycle content are listed in the following table.

Material	CO ₂ footprint, virgin materials (kg/kg)	CO ₂ footprint, recycled material (kg/kg)	Recycle content (%)	Actual CO ₂ footprint (kg/kg)
Aluminum 12 alloys	12	2.6	43	8.0
Cast iron	2.4	0.67	67	1.2
Phenolics	1.9	—	0	1.9

The carbon footprint of the aluminum pot with 43% recycle content is:

$$0.8 \times 8 + 0.1 \times 1.9 = 6.5 \text{ kg.}$$

That of the cast iron pot with 67% recycled content is:

$$2.4 \times 1.2 + 0.1 \times 1.9 = 3.1 \text{ kg.}$$

The cast iron pot has a carbon footprint that is 52% less than that of the aluminum one, despite its greater mass.

Special topic: adjusting for country-specific energy mixes. If you want to know how much energy it takes to make a material, you can measure it. If you want to know the carbon consequence, you need to know where the energy came from. The carbon footprint of materials depends on the energy mix in the country in which it was produced. Energy mix (Appendix B, Table B11) varies from country to country: the extensive use of bio-fuels in Brazil, of geothermal electricity generation in Iceland, of hydroelectricity in Norway, and of nuclear power in France significantly changes the carbon footprints of materials made and used there. Ideally, we would like country-specific values for embodied energy and carbon footprints but such data do not exist. It does not feel right to ignore the country-specific aspect of material production and product use just because we lack data for it. Is there some sort of fix—an approximate correction—that could be applied to the data we *do* have to accommodate this?

If we assume that the *energy* to make a material is country independent, we can correct the *carbon footprint* to match the country-specific energy mixes. We take oil as the norm for hydrocarbons and electricity supply from a gas-fired power station with 38% efficiency as the norm for electrical power. Table B10(b) of Appendix B lists the correction factor (multiplier) to be applied to carbon footprints from fuels and electrical energy. The correction factor for actual energy mixes can then be found by linear interpolation. The two examples that follow show how these can be used.

Example: carbon footprint of products using bio-fuel

Transport within Brazil makes extensive use of bio-fuel. If the typical fuel mix is 85% bio-diesel and 15% conventional diesel, what is the carbon footprint of transport by 40-tonne truck in Brazil?

Answer. Bio-diesel can be credited with zero carbon emission because the carbon it contains was itself drawn from the atmosphere when the feedstock from which it is derived was grown. Table B9, Appendix B, gives the carbon emissions for a 40-tonne truck as 0.063 kg CO₂/tonne•km. Interpolation gives the correction factor for 85% bio-diesel:

$$0.85 \times 0 + 0.15 \times 0.063 = 0.0095 \text{ kg CO}_2/\text{tonne} \cdot \text{km.}$$

The carbon footprint of transport by 40-tonne truck is reduced from 0.063 to 0.0095 kg CO₂/tonne•km by the bio-diesel addition.

Example: hydro-aluminum

Greenland's glaciers are retreating because of global warming, increasing the potential for generating hydroelectric power from melt water. Table B2 lists the carbon footprint for aluminum production using conventional electric power as 12 kg/kg. It is proposed to establish an aluminum production facility in the most promising of Greenland's fjords. Doing so will create the need for additional shipping to transport bauxite to Greenland and aluminum back to where it will be used; the estimate is 20 tonne•km of sea freight per kilogram of delivered aluminum. What do these aspects of production do to the carbon footprint of the aluminum?

Answer. Table B10(b), Appendix B, gives the carbon footprint of hydropower relative to that of conventional fossil fuel-sourced electricity as 0.06, reducing the production footprint to:

$$12 \times 0.06 = 0.72 \text{ kg/kg.}$$

Table B9 gives the carbon footprint of bulk sea freight as 0.014 kg/tonne•km. The additional 20 tonnes•km of sea transport creates an additional carbon footprint of:

$$20 \times 0.014 = 0.28 \text{ kg/kg,}$$

giving a total of 1.0 kg/kg as the final footprint of the aluminum. On this basis the Greenland scheme looks attractive. But water flow from glacial melt fluctuates with the seasons. If the plant is to meet delivery obligations, it may need backup power from more conventional sources, with inevitable increase in emissions.

6.8 Summary and conclusions

You can't answer technical questions without numbers. "Choice X is better than choice Y ..." is a statement that is on solid ground only if you have data to back it up. Concern for the environment, today, sometimes leads to statements based more on emotion than reason, clouding issues and breeding deception. So, boring though numbers can be, they are essential for what follows.

To use numbers, you have to know where to find them, what they mean, and how accurate (or inaccurate) they are. This chapter introduced those used later in this book, presenting them as bar charts that display relationships and correlations. The thing to remember about them is that their precision is low. If you are going to

base decisions on their values, make sure that the decision still stands if the numbers are wrong by $\pm X\%$, where X is the standard deviation of the data. Such uncertainty does not prevent decision-making, provided its presence is recognized and allowed for. The charts help here. When the bars or bubbles overlap, the differences between the materials they represent are not significant. When they don't overlap, there is a significant difference.

The poor coverage of eco-property data generates two further challenges. The first is that some property values for some materials are simply not there; no one has measured them yet. It then becomes necessary to estimate them. Useful correlations exist between carbon footprint and embodied energy and between both of these and ore grade and material price. These provide sanity checks for existing data and ways of making approximate estimates when no real measurements are available.

The second difficulty arises from the differences in mix of hydrocarbon fuel and of renewable energy in the electricity generation from country to country. These differences mean that carbon footprints of materials made or processed in one country differ from those of another even though the energies involved are the same. The carbon footprints of transport, too, are country specific. We lack direct measurements that allow comparisons between countries, so we have to fall back on adjusting the data we *do* have by applying approximate correction factors, as explained in this chapter.

6.9 Further reading

General engineering properties of materials

- Ashby, M.F., Shercliff, H.R. and Cebon, D. (2019) "Materials: engineering, science, processing and design", 4th edition, Butterworth Heinemann, Oxford, UK. (*An elementary text introducing materials through material property charts, and developing the selection methods through case studies.*)
- Budinski, K.G. and Budinski, M.K. (2010) "Engineering materials, properties and selection", 9th edition, Prentice Hall, New York. (*An established materials text that deals with both material properties and processes.*)
- Callister, W.D. and Rethwisch, D.G. (2014) "Materials science and engineering, an introduction", 9th edition, John Wiley, New York. (*A well-respected materials text, now in its 7th edition, widely used for materials teaching in North America.*)
- Dieter, G.E. (1999) "Engineering design, a materials and processing approach", 3rd edition, McGraw-Hill, New York. (*A well-balanced and respected text focusing on the place of materials and processing in technical design.*)
- Farag, M.M. (2013) "Materials and process selection for engineering design", 3rd edition, CRC Press, Taylor and Francis, London, UK. (*A Materials Science approach to the selection of materials.*)

Shackelford, J.F. (2014) "Introduction to materials science for engineers", 8th edition, Prentice Hall, NJ. (*A well-established materials text with a design slant.*)

Material property charts

Ashby, M.F. (2017) "Materials selection in mechanical design", 5th edition, Butterworth Heinemann, Oxford, UK. (*An advanced text developing material selection methods in detail.*)

Geo-economic data

Food and Agriculture Organization of the United Nations (FAOSTAT) (2019) <http://faostat.fao.org/site/567/default.aspx#anchor> (*Data up to 2016 for the annual world production of agricultural crops, including natural fibers and rubber.*)

Geokem (accessed 2019) <http://www.geokem.com/global-element-dist1.html>. (*Global distribution of the elements.*)

US Geological Survey (2018) <https://minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf>. (*Data for metals and minerals.*)

Material production: embodied energy, CO₂ footprint and water usage, engineering materials

Aggregain, (2019), The Waste and Resources Action Program (WRAP), <http://www.wrap.org.uk/content/constructioncontractors> (*Data and an Excel-based tool to calculate energy and carbon footprint of construction materials.*)

Alcorn, A. (2003) "Embodied Energy and CO₂ Coefficients for New Zealand Building Materials", Centre for Building Performance Research, ISBN 0-475-11099-4 Report Series, https://www.victoria.ac.nz/architecture/centres/cbpr/resources/pdfs/ee-co2_report_2003.pdf.

BCA (Accessed 2019), British Cement Association "Publications index" (<https://www.thenbs.com/PublicationIndex/documents?Pub=BCA>). (*Fact-sheets for sustainable design with cement and concrete.*)

BREEAM (2019) The Building Research Establishment, <https://www.breeam.com/>. (*Sustainability assessment methods for planning projects, infrastructure and buildings.*)

CES EduPack Eco Design database (2019a), Granta Design, Cambridge, UK, www.grantadesign.com/education. (*A major database of environmental properties of engineering materials.*)

CES EduPack Eco Design database (2019b), Granta Design, Cambridge, UK, www.grantadesign.com/education. (*Limited data for the eco-aspects consumer electronics.*)

Chemlink Australasia (1997) <http://www.chemlink.com.au/mag&oxide.htm>. (*Eco data for magnesium.*)

EcoInvent (2019) EcoInvent Centre, Swiss Centre for Life Cycle Inventories, <https://www.ecoinvent.org/database/database.html>. (*A massive compilation of environmental data for materials hosted by the University of Delft.*)

- EcoInvent 3.5 (2019) EcoInvent Centre, Swiss Centre for Life Cycle Inventories, www.ecoinvent.org.
- Energy Information Administration (2008) (www.eia.doe.gov) (*Official energy statistics from the US government.*)
- European Reference Life Cycle Database (ELCD) (2018), of the Sustainability Unit of the Joint Research Centre of the European Commission, Petten, the Netherlands. <https://eplca.jrc.ec.europa.eu/ELCD3/datasetDownload.xhtml>.
- REET (accessed 2019) Argonne National Laboratory and the US Department of Transport, <https://reet.es.anl.gov/>. (*Software for analyzing vehicle energy use and emissions.*)
- Hammond, G. and Jones, C. (2011) "Inventory of Carbon and Energy (ICE)", Department of Mechanical Engineering, University of Bath, Bath, UK. <https://researchportal.bath.ac.uk/en/publications/embodied-energy-and-carbon-in-construction-materials>.
- Holtzhausen, H. J. (2007) "Embodied energy and its impact on architectural decisions", WIT Transactions on Ecology and the Environment, Vol 102, WIT Press. <https://www.witpress.com/Secure/elibrary/papers/SDP07/SDP07036FU1.pdf>.
- IdeMat (2019) Faculty of Design, Engineering and Production, Delft University of Technology, Delft, Netherlands, <http://idematapp.com/>. (*Environmental attributes of materials — one of the first in the game. There is a variant of it that includes an estimate of eco-cost.*)
- International Aluminum Institute (Accessed 2019) "Life cycle inventory of the worldwide aluminum industry" (www.world-aluminum.org/).
- Kuehr, R. and Williams, E., editors (2003) "Computers and the environment: understanding and managing their impacts", Kluwer Academic Publishers and United Nations University. (*A multi-author monograph on the environmental aspects of electronic devices, with emphasis on the WEEE regulations relating to end of life. Chapter 3 deals with the environmental impacts of the production of personal computers.*)
- Lafarge Cement, Sustainability (2015), Lafarge Cement UK, Manor Court, Chilton, Oxon, OX11 0RN. <https://www.lafargeholcim.com/climate>. (*Steps to reduce the carbon footprint of cement.*)
- MEEUP (2005) "Methodology study eco-design of energy-using products", European Commission Report. file:///C:/Users/User/Downloads/finalreport1_en.pdf.
- NREL (2019) "U.S. Life Cycle Inventory Database", US Department of Energy, <https://www.nrel.gov/lci/>. (*A database to support Life Cycle Assessment.*)
- Plastics Europe (2019) <https://www.plasticseurope.org/en/resources/eco-profiles>. (*Eco-profiles of polymers.*)

Material shaping and joining processes

- Allen D.K. and Alting, L. (1994) "Manufacturing processes Reference Guide", student manual, Brigham Industrial Press. <https://books.industrialpress.com/manufacturing-processes-reference-guide.html>.

- BBC (accessed 2019) "Paint calculator", <http://www.bbc.co.uk/homes/diy/paintcalculator.shtml>.
- Bookshar, D. (accessed 2019) "Energy consumption of pneumatic and DC electric assembly tools", Stanley Assembly Technologies, 5335 Avion Park Drive, Cleveland, OH 44143. <https://www.stanleyengineeredfastening.com/product-brands/assembly-technologies>.
- Bradley, R. Griffiths, A., and Levitt, M. (1995) CIRIA, Construction Industry Research and Information Association, Vol. F; "Paints and coatings, adhesives and sealants".
- Bralla, J. "Handbook of manufacturing processes — How products, components and materials are made", Industrial Press. <https://books.industrialpress.com/handbook-of-manufacturing-processes.html>.
- Centre for Building Performance Research (2003, accessed 2019) "EE & CO₂ coefficients for New Zealand building materials" and "Table of embodied energy coefficients", at http://www.victoria.ac.nz/cbpr/documents/pdfs/ee-co2_report_2003.pdf and <http://www.victoria.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf>.
- CES EduPack Eco Design database (2019), Granta design, Cambridge, UK. www.grantadesign.com/education. (*Data for the eco-aspects of shaping, joining and finishing operations.*)
- Dahlquist, S. and Gutowski, T. (2004) "Life cycle analysis of conventional manufacturing techniques: sand casting", Proc. 2004 ASME IMECE meeting, Anaheim, CA. <http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1652682>.
- EcoInvent (2019), EcoInvent centre, Swiss centre for life cycle inventories, <https://www.ecoinvent.org/database/database.html>. (*A massive compilation of environmental data for materials hosted by the University of Delft.*)
- Energy Information Administration, 2008 Energy Information Administration (2008) (www.eia.doe.gov). (*Official energy statistics from the US government.*)
- Eurecipe (2016) "Low energy plastics processing best practice guide" (<http://www.iipnetwork.org/eurecipe-low-energy-plastics-processing-best-practice-guide-0>).
- European Reference Life Cycle Database (ELCD) (2018) Of the Sustainability Unit of the Joint Research Centre of the European Commission, Petten, the Netherlands. <https://eplca.jrc.ec.europa.eu/ELCD3/datasetDownload.xhtml>.
- Greene, J.P (2014) "Sustainable plastics", Wiley, New York.
- Groover, M P (2016) "Principles of modern manufacturing", John Wiley & Sons, New York.
- Hammond, G and Jones, C (2011) "Inventory of Carbon and Energy (ICE)", Department of Mechanical Engineering, University of Bath, Bath, UK. <https://researchportal.bath.ac.uk/en/publications/embodied-energy-and-carbon-in-construction-materials>.

Suzuki, T. and Takahashi, J. (2005) The Ninth Japan International SAMPE symposium Nov. 29–Dec. 2. (*A detailed energy breakdown of energy of materials for cars.*)

Thompson, R. (2013) “Sustainable materials, processes and production”, Thames and Hudson, London, UK.

Recycling and end of life

Chemlink Australasia (2018) <http://www.chemlink.com.au/>.

Geokem (2008) www.geokem.com/global-element-dist1.html.

International Aluminum Institute (2000) “Life cycle inventory of the worldwide aluminum industry”, Part 1—automotive, <http://www.world-aluminum.org/>.

Lafarge Cement (2017), Sustainability Report, LafargeHolcim, https://www.lafargeholcim.com/sites/lafargeholcim.com/files/atoms/files/04062018_lafargeholcim-sustainability-report-2017.pdf.

Schlesinger, M.E. (2007) “Aluminum recycling” CRC press, New York.

Sustainable concrete (accessed 2019) <http://www.sustainableconcrete.org.uk/>.

The Nickel Institute North America (2007), Nickel Institute, Toronto, Canada <http://www.nickelinstitute.org/>.

US Geological Survey (2016) “USGS circular 1196, Flow studies for recycling metal commodities in the United States”, <https://pubs.usgs.gov/circ/circ1196/>.

US Geological Survey (2018) <https://minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf>. (Data for metals and minerals.)

Transport carbon footprint and energy

Aviation Environmental Federation (accessed 2019) “Comparison of carbon footprint per passenger.km by car, train, coach and plane in UK”, http://www.aef.org.uk/downloads/Grams_CO2_transportmodesUK.pdf.

Carbon Independent (2009) http://www.carbonindependent.org/sources_ferry.htm (Estimates for carbon emissions from ferries).

Carbon Trust (2015) “Sustainable transport in cities”, <https://www.carbontrust.com/news/2015/01/sustainable-transport-cities/>. (*Adapting transport for sustainable cities.*)

European Environmental Agency (accessed 2019) <https://www.eea.europa.eu/media/infographics/co2-emissions-from-passenger-transport/view> (*CO₂ emissions from passenger transport.*)

European Environmental Agency (accessed 2019) https://www.eea.europa.eu/data-and-maps/daviz/specific-co2-emissions-per-tonne-2#tab-chart_1 (*Comparison of carbon footprint per tonne.km for shipping, truck, and rail transport in Europe.*)

Harvey, L.D.D. (2010) “Energy and the new reality 1: energy efficiency and the demand for energy services”, Earthscan Ltd, London. (*An analysis of energy use in buildings, transport, industry, agriculture, and services, backed up by comprehensive data.*)

- International Chamber of Shipping (2019) International shipping federation annual review, www.marisec.org/.
- International Chamber of Shipping (accessed 2019) <http://www.ics-shipping.org/shipping-facts/environmental-performance/comparison-of-co2-emissions-by-different-modes-of-transport> (Comparison of carbon footprint per tonne.km for shipping, truck, and air transport.)
- Network Rail (accessed 2019) www.networkrail.co.uk/. (*The website of the UK rail track provider with environmental information.*)
- NREL (accessed 2019) National Renewable Energy Laboratory, US Department of Energy, www.nrel.gov/lci. (*US Life Cycle Inventory Database.*)
- Shipping Efficiency (2018) www.shippingefficiency.org/ (Grading energy and CO₂ of ships, responsible for about 3% of global CO₂.)
- Weber, C.L. and Matthews H.S. (2008) “Food miles and the relative impacts of food choices in the United States”, *Environmental Science & Technology* Vol. 42, pp. 3508–3513.

Fuel mix and carbon footprint in electrical energy

- Carbon footprint of electricity generation (accessed 2019) https://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf.
- International Energy Agency (IEA) (2017) “Electricity information” IEA publications, <https://www.iea.org/classicstats/relateddatabases/electricityinformation/>. (*An authoritative source of statistical data for the electricity sector. This is one of a series of IEA statistical publications about energy resources.*)

6.10 Exercises

E6.1. Embodied energy. What is meant by *embodied energy per kilogram* of a metal? Why does it differ from the free energy of formation of the oxide, carbonate, or sulfide from which it was extracted?

E6.2. Ideal and real embodied energy. Iron is made by the reduction of iron oxide, Fe₂O₃, with carbon, and aluminum by the electrochemical reduction of bauxite, basically Al₂O₃. The enthalpy of the oxidation of iron is 7.4 MJ/kg, that of aluminum to its oxide is 30.4 MJ/kg. Compare these with the embodied energies of cast iron and of aluminum, retrieved from Appendix B, Table B2. What conclusions do you draw?

E6.3. Extraction efficiencies (1). Copper, atomic weight 59 kg/kmol, can be extracted from natural copper oxide, CuO. The free energy of formation of CuO is 134 kJ/mol. This much energy *must* be provided to liberate 1 mol of copper from CuO. How does this compare with the reported embodied energy of copper, 59 MJ/kg (Appendix B, Table B2)?

E6.4. Extraction efficiencies (2). Aluminum, molecular weight 27 kJ/kmol, is made by the electrolysis of bauxite, essentially Al_2O_3 , releasing 2 mol of aluminum per mole of bauxite. The free energy of formation of Al_2O_3 is 1640 kJ/mol; this much energy *must* be provided to liberate the 2 mol of aluminum from Al_2O_3 . How does this compare with the embodied energy of aluminum, 190 MJ/kg (Appendix B, Table B2)?

E6.5. Embodied energies (1). Window frames are made from extruded aluminum. It is argued that making them instead from extruded poly(vinyl chloride) (PVC) would be more environmentally friendly (meaning that less embodied energy is involved). If the section shape and thickness of the aluminum and the PVC windows are the same, and both are made from virgin material, is the claim justified? You will find embodied energies and densities for the two materials in Appendix B, Table B2, and Appendix A, Table A2.

E6.6. Embodied energy (2). A range of office furniture includes a chunky hardwood table weighing 25 kg and a much lighter table with a 2.0 kg virgin aluminum frame and a 3.0-kg glass top. Which of the two tables has the lower embodied energy? Use data from Appendix B, Table B2, to find out.

E6.7. Carbon footprints (1). Rank the three common commodity materials *low-carbon steel*, *aluminum alloy*, and *polypropylene* by carbon footprint per unit weight (kg/kg), CO_2 , and carbon footprint per unit volume (kg/m^3), $\text{CO}_2\rho$, where ρ is the density, using data from Appendix A, Table A2, for density and Appendix B, Table B2, for carbon footprint in kg/kg.

E6.8. Carbon footprints (2). A bicycle design has an aluminum alloy frame weighing 11 kg; a medium-carbon steel wheel set, total weight 1.4 kg; and tires, grips, and saddle, all butyl rubber, weighing 0.9 kg. What, approximately, is the carbon footprint of the materials of the bike? How does it compare with the carbon footprint of 1 L of gasoline? You will find eco-data for the materials in Appendix B, Table B2, and data for gasoline in Table B10.

E6.9. Carbon footprint and embodied energy. Make a bar chart of CO_2 footprint divided by embodied energy, using data Appendix B, Table B2, for:

- cement
- low-carbon steel
- copper alloys
- titanium alloys, and
- aluminum alloys

Which material has the highest ratio? Why?

E6.10. Sequestered carbon. The embodied energies and CO_2 footprints for softwood and paper do not include a credit for the energy and carbon stored in the wood itself, for the reasons explained in the text. Recalculate these,

crediting them with sequestering energy and carbon by subtracting out the stored contributions (take them to be 25 MJ/kg and 2.8 kg CO₂/kg) using data from Table B2, Appendix B. Can they now be credited with storing more energy and carbon than it takes to harvest and process them?

E6.11. Precious metals (1). A chemical engineering reactor consists of a stainless-steel chamber and associated pipework weighing 3.5 tonnes, supported on a mild steel frame weighing 800 kg. The chamber contains 20 kg of loosely packed alumina spheres coated with 200 g of palladium, the catalyst for the reaction. Compare the embodied energies of the components of the reactor, using data from Appendix B, Tables B2 and B3(a).

E6.12. Precious metals (2). You have developed an environmental conscience. You have also met the girl of your dreams whom you are about to marry. The wedding ring you would like to buy for her is 24 carat (100%) gold and weighs 10 g. She prefers one made of a 50–50 platinum–rhodium alloy weighing 15 g. How different are the embodied energies of the two rings? (Table B3(a) of Appendix B has data for precious metals.)

Since this is a silly question already, we'll add the lightbulb test. With a conversion efficiency of 0.38 for primary energy to electrical energy, for how many hours could you run a 10-W LED lamp on the energy saved if your girlfriend is willing to settle for the gold ring? (Remember 1 kWh = 3.6 MJ.)

E6.13. Electronics. A product line of portable radios has 4 AA Ni–Cd batteries, a small integrated circuit weighing 100 g, two speakers with alnico magnets weighing 700 g, a transformer weighing 500 g, and ABS casing weighing 400 g. Alnico has an embodied energy of 89 MJ/kg. Data for ABS and for the other electrical components can be found in Appendix B, Tables B2 and B4. Which of these makes the largest contribution to the embodied energy?

E6.14. Process energies. What is meant by the process *energy per kilogram* for casting a metal? Why does it differ from the latent heat of melting of the metal?

E6.15. Ideal and real process energies. The melting point of an aluminum alloy is 570°C. Its specific heat $C_p = 940 \text{ J/kg} \cdot \text{K}$ and its latent heat of melting $L = 390 \text{ kJ/kg}$. Estimate the theoretical minimum energy to melt alloy and compare this with the casting energy range listed in Table B6 of Appendix B. Take room temperature to be 20°C. What do you deduce from the comparison?

E6.16. Process carbon footprints (1). A bicycle maker manufactures frames from drawn low-carbon steel tubing by gas welding, followed by the application of a baked-on paint coating. One frame weighs 11 kg, the length of weld is 0.4 m, and the surface area of the frame is 0.6 m². Calculate the carbon footprints of material and processing, using data for steel from

Appendix B, Table B2, and those for processing from Table B6 (use the data roll forming, forging as a proxy for tube drawing), using the mean values of the ranges listed there. Sum them to give a final energy total. Which contribution is the largest?

E6.17. Process carbon footprints (2). A cast iron cistern cover is cast to its initial shape and then rough-machined to final shape, removing 5% of its mass. If the initial casting weighed 16 kg, what, approximately, is the carbon footprint associated with the material and the processing of the cover? Which step contributes the most? Appendix B, Tables B2 and B6, contain the necessary data.

E6.18. Using process energies. A large connecting rod is cast from an aluminum alloy. The bores are finished by light machining, removing 0.05 kg of the metal. The finished connecting rod weighs 3.2 kg. It is suggested that machining the connecting rod from a solid rolled aluminum blank would give a higher-quality product. The starting blank weighs 5 kg. Heavy (coarse) machining is used for all but the finishing of the bores. Assuming virgin aluminum is used and that the machinings are not recycled, what is the energy penalty of taking the machine-from-solid option?

E6.19. Material versus processing energies. A low-carbon steel car door skin (the outer panel) of area 0.8 m^2 and thickness 1.2 mm is shaped by deformation processing. It is then given a baked coating on its outer face and assembled using fasteners, requiring 14 of them. Rank the approximate carbon footprint of the material and the process steps. Appendix B, Tables B2 and B6, contain the necessary data. Take the density of low-carbon steel to be 7800 kg/m^3 .

E6.20. Recycle energies (1). Exercise E6.5 compared the embodied energies of virgin aluminum and PVC window frames of the same dimensions (and thus material volume). In reality, the aluminum frame is made not of virgin materials but of 100% recycled aluminum. Recycled PVC is not available, so the PVC window continues to use virgin material. Which frame now has the lower embodied energy? Appendix B, Tables B2 and B7, contains data for virgin and recycled materials.

E6.21. Recycle energies (2). It is found that the quality of the window frame of Exercise E6.20, made from 100% recycled aluminum, is poor because of the pickup of impurities. It is decided to use aluminum with a “typical” recycled content of 43% instead. The PVC window is still made from the same volume of virgin material. Which frame now has the lower embodied energy?

E6.22. Recycle content (1). The aluminum–glass table of Exercise E6.6 is, in fact, made from aluminum and glass with a typical recycled content. As in the earlier exercise, the frame weighs 2.0 kg and the glass top weighs 3.0 kg.

How much difference does this make in its embodied energy? Appendix B, Tables B2 and B7, contains data for virgin and recycled materials.

E6.23. Recycle content (2). The chassis and casing for a high-end portable computer are milled from a solid high-strength aluminum alloy block initially weighing 2 kg. In doing so 80% of the block is removed by rough machining and a further 5% by finish machining. How does the machining energy compare with the initial embodied energy of the block if made from virgin aluminum? If instead 100% recycled aluminum is used for the block, does the ranking change? Appendix B, Tables B2, B6, and B7, contains the relevant data.

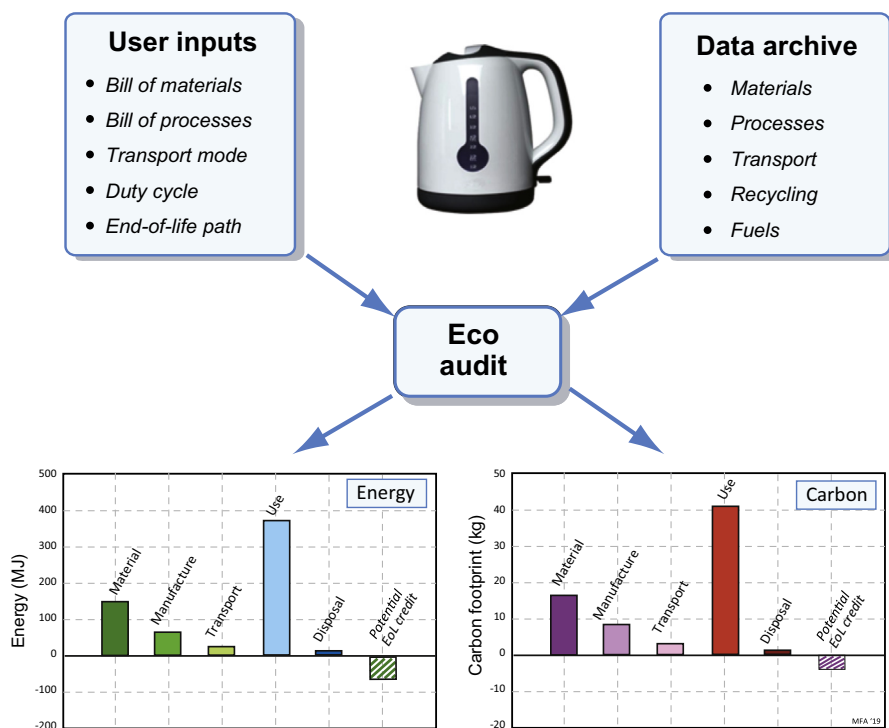
E6.24. Transport energies (1). Cast iron scrap is collected in Europe and shipped 19,000 km to China where it is recycled. The energy to recycle cast iron is 8.5 MJ/kg. How much does the transport stage add to the total energy for recycling by this route? Is it a significant increase? Energies for freight transport are listed in Appendix B, Table B8(a).

E6.25. Transport energies (2). Bicycles weighing 15 kg are manufactured in South Korea and shipped to the west coast of the United States, a distance of 9000 km. On unloading they are transported by 32-tonne truck to the point of sale, Chicago, a distance of 2900 km. What is the transport energy per bicycle?

To meet Christmas demand, a batch of the bicycles is air freighted from South Korea directly to Chicago, a distance by air of 10,500 km. What is the transport energy then? Energies for freight transport are listed in Appendix B, Table B9(a).

E6.26. Transport energies (3). You are an assistant professor of history at a German university and an active member of the Green Party. You have just been appointed to a chair of history at the University of Sydney, Australia, 24,000 km away. You have a large library of books, which you cherish. The total weight of the books is 1200 kg. You could send them by sea freight, but that would take months and entail a risk of damage. Federal Express could air freight them and they would get there before you, safe and sound. Weigh up the environmental consequences of these two options in terms of carbon release to atmosphere. Energies for freight transport are listed in Appendix B, Table B9(a).

Eco-audits and eco-audit tools



CONTENTS

- 7.1 Introduction and synopsis
- 7.2 Eco-audits: energy and carbon fingerprints of products
- 7.3 The practicalities: how to do an eco-audit
- 7.4 The end-of-life credit conundrum: analyzing recycle credits
- 7.5 Circularity: eco-audits with recycling
- 7.6 Computer-aided eco-auditing
- 7.7 Summary and conclusions
- 7.8 Further reading
- 7.9 Exercises

7.1 Introduction and synopsis

An *eco-audit* is a fast, initial assessment of the energy demands of the carbon emissions of the life of a product. It identifies the phase of life—material, manufacture, transport, use, disposal—that carries the highest demand for energy or creates the greatest burden of CO₂. It points the finger, so to speak, identifying where the problems lie. One phase of life, in eco-terms, is often dominant, accounting for more than 75% of the energy and carbon totals. This difference is often so large that the imprecision in the data and the ambiguities in the modeling, discussed in Chapter 3, are not an issue; the dominance remains even when the most extreme data values are used. It then makes sense to focus first on design to tackle this dominant phase, since it is here that the potential gains are greatest. There is

more to it than this; ameliorating one phase of life may augment another. We'll get to that, but for now, focus on the simple audit.

The main purpose of an eco-audit is one of *comparison*, allowing alternative design choices to be explored rapidly. To do this it is unnecessary to include the last nut and bolt—indeed, with the exception of electronics and precious metals, it is usually enough to account for the few components that make up 95% of the mass of the product, assigning a “proxy” energy and CO₂ to those that are not included directly. The output, of course, is approximate; but if the comparison reveals differences that are large, robust conclusions can be drawn.

This chapter introduces the eco-audit method and the data needed to implement it. The next illustrates its use with a set of case studies. Software packages now exist that make the job easier.

7.2 Eco-audits: energy and carbon fingerprints of products

Chapter 3 introduced the materials life cycle. Materials are created from ores and feedstock and made into products that are distributed and used. Products have a finite life, at the end of which they become scrap. The materials they contain, however, are still there; some can be reused, reconditioned, or recycled to provide further useful service. *Life-cycle assessment* (LCA) traces this progression, documenting the resources consumed and the emissions excreted during each phase of life. The output is a sort of biography, documenting where the materials have been, what they have done, and the consequences of this for their surroundings. In particular it documents the energy consumed and the carbon emitted to the atmosphere by the product over its life.

Responsible design, today, aims to provide safe, affordable services while minimizing the drain on resources and the release of unwanted emissions. To do this, the designer needs feedback on the eco-profile of the design (or redesign) as it progresses. To be useful, this feedback must be fast, allowing quick “what if?” exploration of the consequences of alternative choices of material, use pattern, and end-of-life choice. A full LCA is not well adapted for this task; it is slow and expensive. *Streamlined LCA* and the *eco-audit methods* have evolved to fill the gap.

These methods are approximate, but the distinctions that they draw can be sufficiently sharp to distinguish the most damaging phases of product life and the changes that can improve it. The output can be thought of as an energy and carbon *fingerprint*: the incriminating patterns of eco-hits made by a particular design. The carbon emissions (and those of sulfur and nitrogen) do not scale exactly with energy, but since so much energy we use is derived from hydrocarbon fuels, the energy fingerprints are a sort of proxy for the others.

Fig. 7.1 introduces the output of an eco-audit. Each bar describes, for a given product, the energy consumed in each phase of the life cycle: material production,

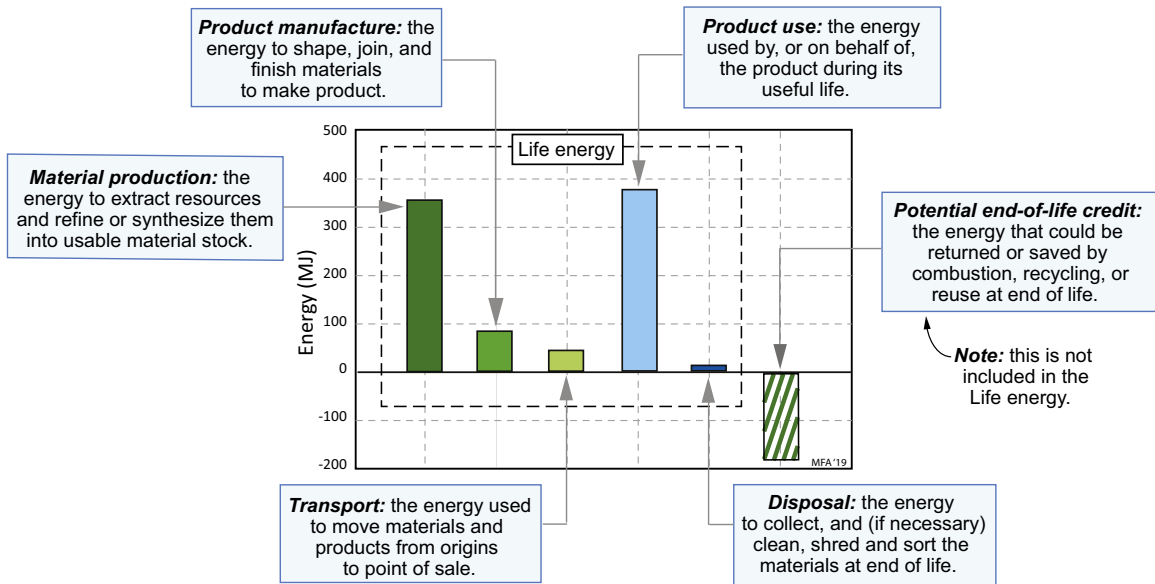


FIGURE 7.1 *The output of an eco-audit.*

product manufacture, product use, product disposal at end of life, and the transport in between. The carbon and other emissions follow a similar pattern, not exactly, but fairly closely. There are two bars for end of life, a complication explained in a moment. The total life energy is the sum of the five left-hand bars, boxed in the figure.

The first bar shows the mass-weighted sum of the embodied energies of the materials in the product. The second is an estimate of the energy to manufacture the product. Transport is involved; the third bar sums the energy involved in this. Most products consume energy during their active life; the fourth bar describes this. Some products (photocopiers, for example) consume both energy and materials (paper, toner) during use. These are treated here as an energy contribution to the use phase. The fifth bar, almost always very small, is the energy to collect the product at end of life and clean, shred, and sort its materials. The sum of these five bars gives an estimate of the life energy.

There is one more bar. A designer wishing to minimize the eco-impact of a product may wish to use recycled materials, thereby lowering the life energy. The eco-audit gives credit for this, appearing as a reduced height of the materials bar. The same designer may also wish to structure the design so that it is easy to dismantle for recycling and choose materials that recycle well. That cannot be included as a credit in the life energy because credit has already been awarded for use of recycled materials at start of life and because it remains a future option that may not be adopted. Yet the eco-audit should signal the energy return that is

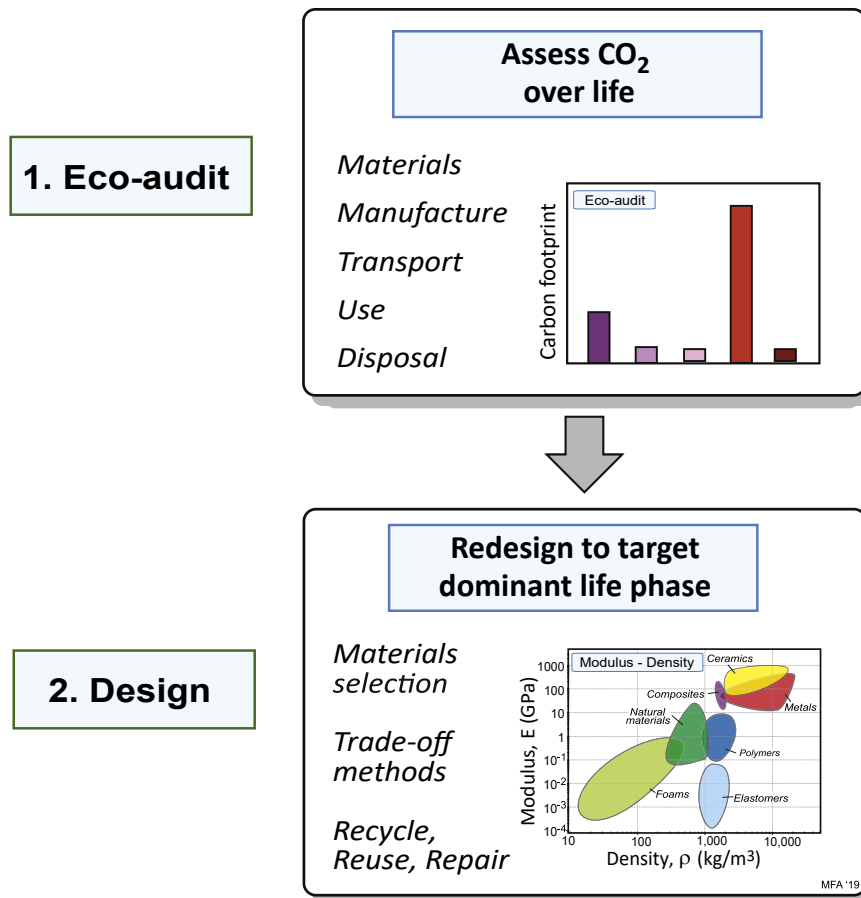


FIGURE 7.2 Eco-design of products starts with an analysis of the energy and carbon profile of each life phase. Subsequent action depends on which phase is the biggest culprit.

enabled by allowing recycling. That is what the last bar, hatched in color, describes.

To make an eco-audit you need *data*, data for the embodied energies and carbon footprints of the materials involved, and the same for the manufacturing processes, the energy and carbon profile of the transport systems, and the energy consumed by the product during the use phase of its life. Appendix B provides them.¹

The eco-audit is the first step. Fig. 7.2 suggests the subsequent action: redesign to target the most damaging phase of life. Materials selection becomes a key player

¹Data are provided in a more accessible format in software designed for eco-auditing purposes, such as the eco-database of the CES EduPack (2019) Materials Selection Software (www.grantadesign.com/education).

here: selection to minimize the embodied energy and carbon footprint of the product, selection to minimize mass, selection to allow a more circular use of materials in the economy. Implementation requires tools. Two tools are needed, one to perform the eco-audit sketched in the upper part of Fig. 7.2, the other to enable the analysis and selection implied by the lower part. The first, the eco-audit tool, is described in this chapter and the next. The second, that of optimized selection, is the subject of Chapters 9 and 10.

7.3 The practicalities: how to do an eco-audit

The cover picture of this chapter shows the procedure for the eco-audit of a product. The inputs are of two types: *User inputs* and (archived) *material data*. The first step is to assemble a *bill of materials*, *process choice*, *transport requirements*, *duty cycle* (the details of the energy and intensity of use), and *disposal route*, shown at the top left. Second, data for embodied energies, process, recycle, unit transport, and use energies and carbon intensities are drawn down from digital or hard-copy archives (Appendix B). The eco-audit tool (you, or a digital equivalent) combines the information to present the energy or carbon fingerprints as bar charts and in tabular form. The method is best illustrated by an example of extreme simplicity: the life cycle of a polyethylene terephthalate (PET) water bottle.

A single-use water bottle. One brand of bottled water—we will call it *Alpure*—is particularly popular in the United Kingdom. It is sold in 1-L virgin PET bottles with virgin polypropylene caps. One empty bottle weighs 40 g; its cap weighs 1 g. The bottles and caps are molded, filled with water at a source of sparkling purity located in the French Alps not far from Évian, and transported 1030 km to London, England, by six-axle (40-tonne) truck. Once there, they are refrigerated, on average for 2 days, before appearing on the tables of cafés where they are consumed, adding significantly to the bill. The cafés have no environmental policy or conscience: the empty bottles are sent to a waste disposal site where they are incinerated (Fig. 7.3). What does the carbon fingerprint of *Alpure* water look like?

The eco-audit procedure has four steps, described here for carbon emissions. The audit for energy follows the same steps:

Step 1. Materials and manufacture: A bill of materials is drawn up, listing the mass of each component, the material of which it is made, and the process used to make it (see box in Fig. 7.3). Data for the CO₂ equivalent (CO_{2,eq}; kg/kg) per unit mass for each material are retrieved from the database, here, the data sheets of Appendix B. Multiplying the carbon footprint of material and process by the mass of each component and summing gives 0.11 kg CO_{2,eq} for the materials, 0.05 kg CO_{2,eq} for the processing, and a grand total of 0.16 kg CO_{2,eq} per bottle.

Step 2. Transport: The bottles are filled near Évian (combined weight 1.04 kg) and transported to London, a distance of 1030 km. The carbon footprints of transport modes are listed in Appendix B, Table B9; that for

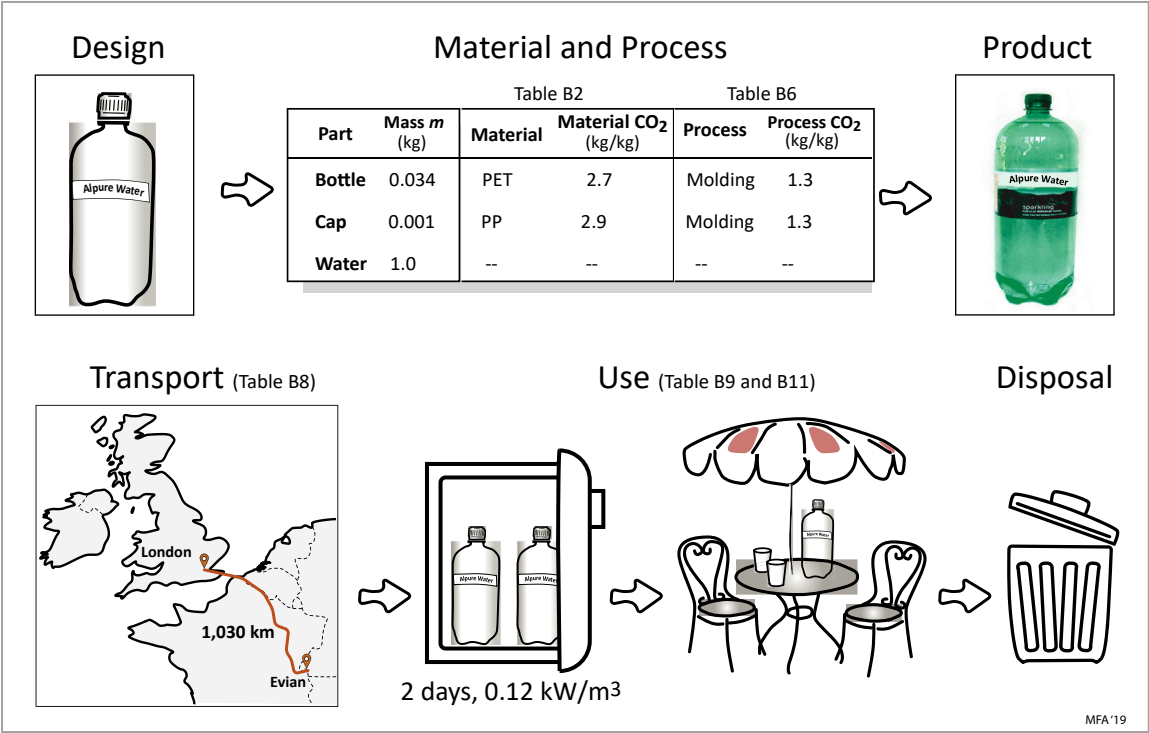


FIGURE 7.3 Polyethylene terephthalate (PET) water bottle: the story line, with pointers to the tables in Appendix B where the data are listed. PP, polypropylene.

the six-axle truck used in this example is 0.063 kg CO_{2,eq}/tonne·km. Combining these numbers we find transport carbon to be 0.068 kg CO_{2,eq} per bottle.

Step 3. The use phase: The PET bottle is a static product. It doesn't consume energy itself but energy is consumed on its behalf via refrigeration. The baseline power requirements for A-rated appliances are 0.12 kW/m³ for refrigeration at 4°C and 0.15 kW/m³ for freezing at −5°C, so refrigerating 1 m³ for 2 days takes 20.7 MJ electrical power. How much fridge volume does a 1-L bottle occupy? Here we need a quick estimate: 10 cm × 10 cm × 50 cm (0.005 m³) is certainly enough, so the energy to keep the one bottle cold for 2 days is 0.1 MJ. To this baseline steady-state energy we add the energy $mC_p \Delta T$ to cool the bottle and contents, mass m , from room temperature (20°C), an interval of $\Delta T = 16^\circ\text{C}$, where C_p is the specific heat. The specific heat of water is 4200 J/kg·°C (that of the bottle

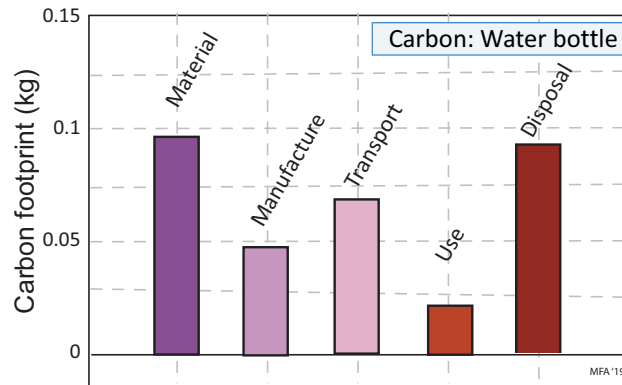


FIGURE 7.4 The carbon fingerprint of the polyethylene terephthalate water bottle when incinerated at end of life.

itself is negligible), giving a cooldown contribution of 0.084 MJ, and a total, rounded, of 0.18 MJ per filled bottle. Converting this to an oil-equivalent energy by dividing by an energy-conversion efficiency at the power plant of 33% gives an oil equivalence of 0.55 MJ. The associated carbon, when the primary energy source is oil, is 0.07 kg CO_{2,eq} per MJ (Table B9), giving a use-carbon contribution of 0.04 kg CO_{2,eq} per bottle.

Step 4. Disposal: If you incinerate plastic, the carbon it contains is released into the atmosphere as CO₂. The carbon footprint for combustion of PET is 2.3 kg/kg (Table B8), so burning one bottle releases 0.092 kg of CO_{2,eq}. In the past, the use of recycled plastics for food and drink containers was not permitted. This has now changed, so a degree of material circularity (Chapter 13) is now possible and practiced.

The output: a product fingerprint. The individual carbon footprints for each stage of life appear in Fig. 7.4; the pattern they form is the product fingerprint—its characteristic distribution of emissions across life. The two largest contributions are those arising from making the PET at the start of life and from incinerating it at the end. The message is clear: recycling bottles rather than burning them addresses both problems, providing lower-carbon material to make new bottles and eliminating the need to incinerate the old ones.

If genuine concern is felt about the eco-impact of drinking Alpure water, then (short of giving it up) it is the bottle that is the primary target. Could it be made thinner, using less PET? (Such bottles are 30% lighter today than they were 15 years ago.) Is there a polymer that is less energy intensive than PET? Could the bottles be reusable and of sufficiently attractive design that people keep them for other purposes? These are design questions that we leave for Chapters 9 and 10.

7.4 The end-of-life credit conundrum: analyzing recycle credits

There are five options for disposal at the end of life: *landfill with or without incineration, combustion with energy recovery, recycling, reengineering, and reuse* (Fig. 4.2). A product at the end of its first life has the ability to return part or all of its embodied energy. This sounds wrong; we've already said that much of the "embodied" energy of a material is not *embodied* at all but is lost as low-grade heat via the inefficiencies of the processing plant. But think of it another way. If the materials of the product are recycled or the product itself is reengineered or reused, a need is filled without drawing on virgin material, thereby saving energy. Carbon release works in the same way, with one little twist: one end-of-life option, combustion with energy recovery, recovers energy, but in doing so it releases yet more CO₂.

If, as an example, the PET bottle of the last section is recycled, the potential end-of-life energy credit is $r(H_m - H_{rc})$, where r is the fraction recycled at end of life, H_m is the embodied energy of virgin PET (Table B2), and H_{rc} is the recycling energy (Table B7). If, instead, it is combusted with heat recovery as electrical power, the potential end-of-life credit is $r(H_m - \eta_{cbst}H_{cbst})$, where H_{cbst} is the heat of combustion (Table B8) and η_{cbst} is the efficiency of conversion of the recovered heat to electrical energy, 25% at best. Each end-of-life choice (except the one chosen by the café selling Alpure) offers some level of energy credit, and all but one offer a carbon credit.

But is it valid to include this credit in the total life energy? To answer that, we have to look at the energy accounting in a little more detail.

Assigning recycle credits. Recycling passes material from one life cycle to the next. In general it takes less energy and releases less carbon to recycle a unit of material than it takes to create the same quantity of virgin material from ores and feedstock—it is this that makes recycling attractive. But is the saved energy and CO₂ to be credited to the first life cycle or the second? It can't be credited to both, since that would be double counting.²

Fig. 7.5 sets the scene. It shows the material flow through three successive product lives, labeled products 1, 2, and 3. Part of the material used to make product 1 is recycled at the end of life 1 and becomes available to make product 2, which is recycled in turn, providing part of the material for product 3.

Focus on product 2. At the start of its life it draws on material created by the recycling of product 1, supplemented by primary (virgin) material created from ores and feedstock. Product 2 enters service and performs its function. At the end of its life, part of its material is recycled and passes to product 3, for which the cycle repeats itself. If product 2 is awarded the credit for receiving recycled material from product 1, it can't also have the credit for delivering it to product 3,

²Hammond and Jones (2010) offer a helpful explanation of the alternatives and their relative merits, paraphrased here.

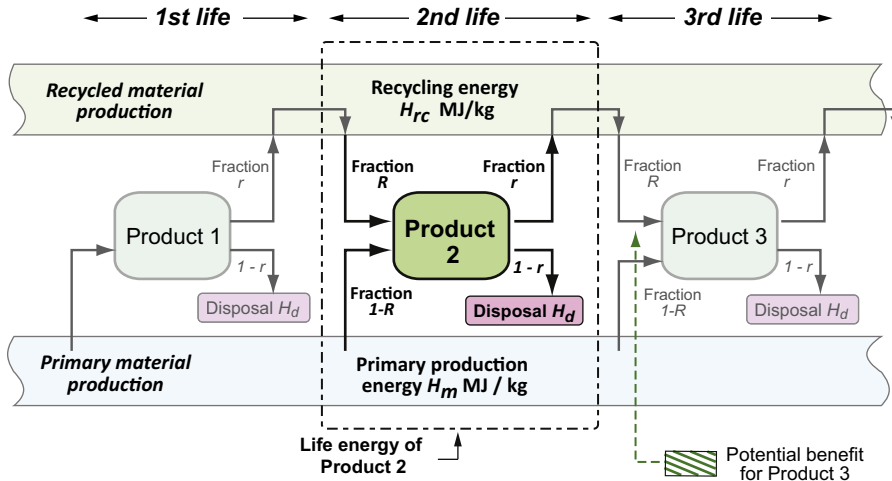


FIGURE 7.5 The material flows during product life. (Adapted from Hammond and Jones (2011).)

because that belongs to product 3. If instead product 1 claims the credit for creating the recyclable material used by product 2, then product 2 loses its start-of-life credit but can now claim one at end of life.

To a designer creating a product, recycling at end of life is a future benefit, one that may not be realized for many years or, indeed, at all. If the concern is for *present* resources, energy demands, and climate-changing emissions, then it makes accounting sense to award product 2 credit for using recycled material at the start of life but award none for passing on material at life's end. It deals with the present, not the future, it avoids double counting and it conforms to the European guidelines on assessing carbon footprint known as PAS 2050 and BSI 2008 (Chapter 5).

But this choice leaves us with a difficulty. One purpose of an eco-audit is to guide design decisions. Designers that strive to design products using recycled materials will feel rewarded by this way of assigning credit. But designers that strive to make disassembly easy and to use materials that recycle well would also want the audit to reflect that, and the method fails to do so. To overcome this, we show the energy and carbon contributions during life as bars of solid colors, and add the potential energy and carbon savings (or penalty) arising from the end-of-life choice as a separate, cross-hatched bar, as in Fig. 7.1 and the cover picture of the chapter.

7.5 Circularity: eco-audits with recycling

The ideas of the last section are best illustrated with an example.

A jug kettle. A 2-kW jug kettle is designed in Britain, manufactured in China, shipped from Shanghai to Los Angeles, and transported by road in a four-axle

(32-tonne) truck to Chicago, where it is sold. The kettle has a life of 1 year before the style-conscious owner replaces it, during which time it is used, on average, three times a day to boil water, taking 2 minutes per boil. At the end of life the materials of the kettle are recycled.

The body of the kettle is made of polypropylene with a recycled content of 20%. The internal frame is made of stainless steel, again with 20% recycled content. The heating element is virgin nichrome (a Ni–Cr alloy). The connecting cable is copper, 50% recycled. There are other components, of course, but they account for only a small fraction of the total mass, and we’ll ignore them. Fig. 7.6 presents the story line.

Step 1. *Materials and manufacture*: The bill of materials appears in the box on Fig. 7.6, which lists the data required for an energy audit, drawn from the indicated tables in Appendix B. A carbon audit follows the same steps and uses the same data tables. Combining the data in the obvious way (multiplying energy/kg, weighted to include the recycle fraction, by the

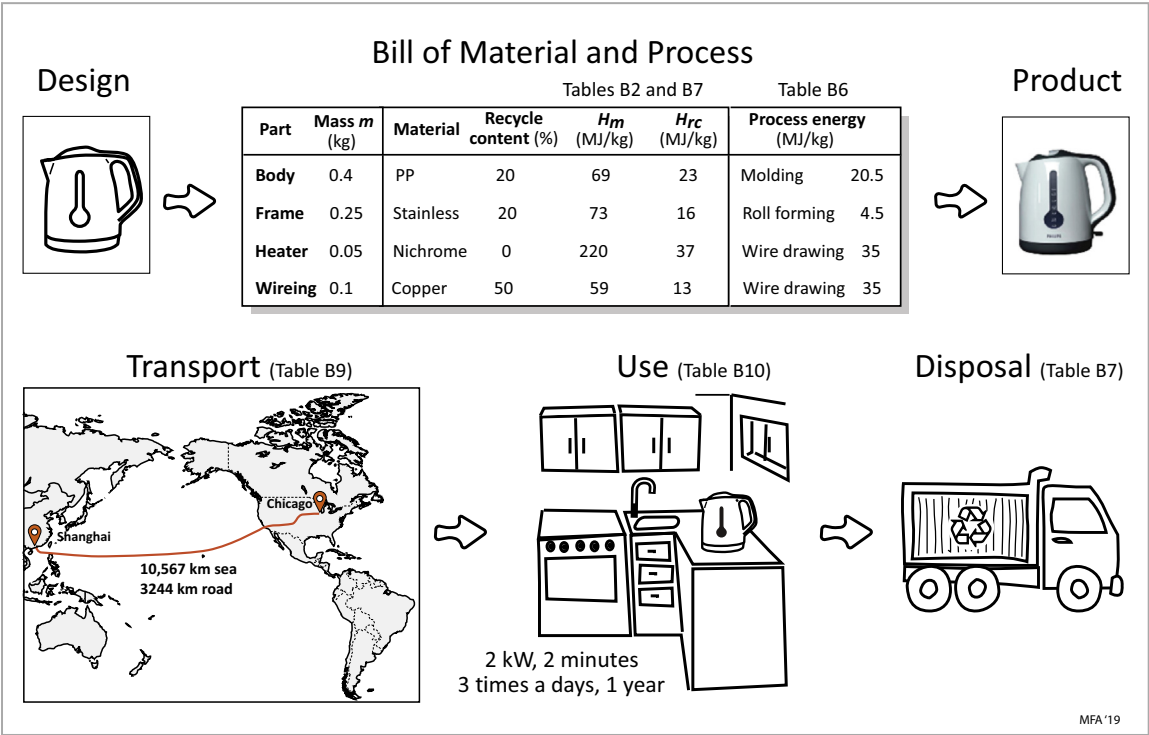


FIGURE 7.6 Jug kettle: the story line. The data are from Appendix B, Tables B2, B6, B7, and B9. PP, polypropylene.

mass and summing) gives the energy consumed by materials and manufacture as 53 and 15 MJ, respectively, per kettle.

Step 2. *Transport*: The kettle, total weight 0.8 kg, is transported by ocean freight (energy 0.18 MJ/tonne·km) to Los Angeles, a distance of 10,570 km, and then driven in a 32-tonne truck (energy 0.94 MJ/tonne·km) to Chicago, a further distance of 3244 km. The combined journey consumes 4.0 MJ.

Step 3. *The use phase*: The 2-kW kettle is used, on average, for 6 minutes per day for 365 days, consuming 263 MJ (electrical) over the single year the purchaser keeps it. To convert this energy to an oil-equivalent value, we divided it by the oil-to-electricity conversion efficiency, which we take to be 0.38, giving the use energy of 690 MJ.

Step 4. *Disposal*: The discarded kettle is transported to the recycling plant with a small energy cost, closing the life cycle.

Step 5. *Potential end-of-life energy credit*: Recycling requires that the product be shredded (Table B7), consuming up to 0.3 MJ/kg. The energy “recovered” by recycling at end of life is the difference between the embodied energy of virgin material and that of recycled material, multiplied by the fraction of the output of the product that is recycled. Assuming this to be a totally unrealistic 100%, the sum of the end-of-life energy credits for the four materials, $m(H_m - H_{rc})$, is 46.5 MJ. Subtracting the shredding energy gives 46.3 MJ. This is a potential future benefit, providing recycled stock for the next life, but it cannot be credited to this life because a credit for using recycled materials has already been awarded.

The output: a product fingerprint. The energy commitment for each stage of life is plotted on the left of Fig. 7.7; the pattern formed is the product fingerprint—its characteristic distribution of emissions across life. The largest contribution is that of the use phase. If energy is to be saved, the kettle must be used less or—perhaps—better insulated, retaining the heat in the water left inside. If the kettle is used for 3 years rather than just 1, the use phase triples, but the others are

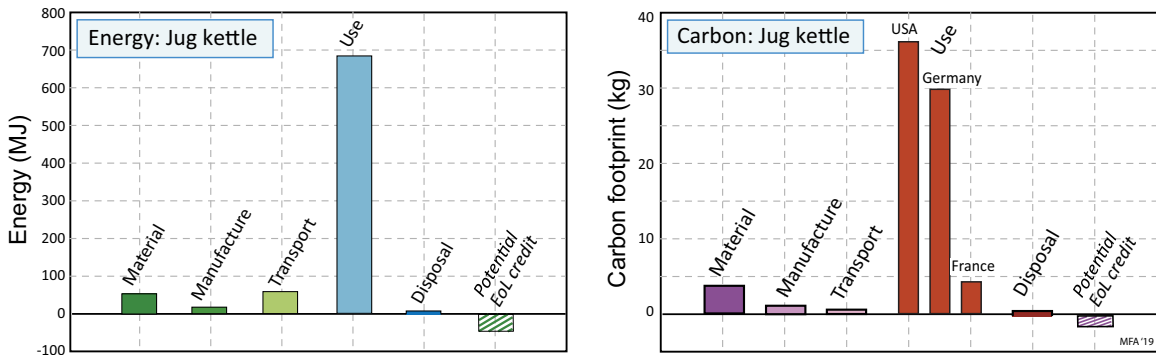


FIGURE 7.7 The energy and carbon fingerprints of the jug kettle. EoL, end-of-life.

unchanged. The energy and carbon fingerprints of many energy-using products are dominated by the use phase, as in this example.

The carbon fingerprint for the kettle appears on the right of Fig. 7.7. The energy to boil water is the same everywhere, but the carbon released in doing so is not. The carbon footprint of electricity depends on the energy source used to make it. In the United States, coal, oil, and gas dominate. Germany depends on these too, but has substantial solar- and wind-based generator capacity. France is 75% nuclear.

7.6 Computer-aided eco-auditing

An eco-audit guides decision-making during design or redesign of a product and it points to the aspects of design that a fuller LCA should examine. Done by hand, like the jug kettle, it can be a little tedious. Computer-aided audit tools remove the tedium by retrieving data from embedded data archives (like that of Appendix B) and doing the underlying calculations once the user inputs are provided. LCA tools such as SimaPro, GaBi, and MEEuP can be used in this way, but they were not designed for it. Others, like the CES eco-audit tool,³ are designed for auditing and are much simpler to use, implementing the procedure suggested by the cover picture of this chapter and delivering the outputs shown there.

7.7 Summary and conclusions

Eco-aware product design has many aspects, one of which is the choice of materials and manufacturing route. Materials are energy intensive; they have high embodied energies and associated carbon footprints. Seeking to use low-energy materials might appear to be one way forward, but this can be misleading. Material choice influences the choice of manufacturing process, it influences the weight of the product and its mechanical, thermal, and electrical characteristics and thus the energy and carbon consequences of its use. Further, it influences the potential for recycling or energy recovery at the end of life. It is the full life that matters, not just one phase of it.

Doing so requires the two-part strategy shown in Fig. 7.2. The first part is the *eco-audit*: a quick, approximate assessment of the distribution of energy demand and carbon emission over life. This guides the actions of the second part: that of design or redesign for eco-efficiency, balancing the influences of the choice over each phase of life—the subject of Chapters 9 and 10. The eco-audit method described here is fast and, with digital help, easy to perform. Although approximate, it delivers information with sufficient precision to guide strategic decision-making. This chapter has introduced the procedure, data, and tools.

³The CES Eco Audit tool is a standard part of the CES EduPack developed by Granta Design, Cambridge, UK (www.grantadesign.com).

The next illustrates their use with case studies. The exercises at the end of both chapters provide opportunities for exploring the methods further.

7.8 Further reading

CES EduPack Eco Design database (2019), Granta Design, Cambridge, UK, www.grantadesign.com/education. (A major database of environmental properties of engineering materials. Includes limited data for eco-aspects of consumer electronics.)

EcoInvent (2019), EcoInvent Centre, Swiss Centre for Life Cycle Inventories, <https://www.ecoinvent.org/database/database.html>. (A massive compilation of environmental data for materials hosted by the University of Delft.)

GaBi 4 (2019) PE International, <http://www.gabi-software.com/uk-ireland/index/>. (An LCA tool that complies with European legislation. It has facilities for analyzing cost, environment, social, and technical criteria and optimization of processes.)

GREET (accessed 2019) Argonne National Laboratory and the US Department of Transport, <https://greet.es.anl.gov/>. (Software for analyzing vehicle energy use and emissions.)

Hammond, G. and Jones, C. (2011) “Inventory of Carbon and Energy (ICE)”, Department of Mechanical Engineering, University of Bath, Bath, UK, <https://researchportal.bath.ac.uk/en/publications/embodied-energy-and-carbon-in-construction-materials>. (A well-documented compilation of embodied energy and carbon data for building materials.)

IdeMat (2019) Faculty of Design, Engineering and Production, Delft University of Technology, Delft, Netherlands, <http://idematapp.com/>. (Environmental attributes of materials — one of the first in the game. There is a variant of it that includes an estimate of eco-cost.)

Matthews, B. (2011) “Java Climate Model” with UCL Louvain-la-neuve, KUP Bern, DEA Copenhagen, UNEP/GRID Arendal, <http://chooseclimate.org>. (An interactive tool to explore the effects of greenhouse gasses on global temperature and sea level.)

MEEUP method (2005) VHK, Delft, Netherlands, www.pre.nl/EUP/. (The Dutch Methodology for Ecodesign of Energy-using Products (MEEUP) is a response to the EU directive on Energy-using products (the EuP directive) described in Chapter 5. It is a tool for the analysis of products — mostly appliances — that use energy, following the ISO 14040 series of guidelines.)

PAS 2050 (accessed 2019) “Specification for the assignment of the life-cycle greenhouse gas emissions of goods and services”, ICS code 13.020.40, British Standards Institution, London, UK. https://webstore.ansi.org/Standards/BSI/PAS20502011?gclid=EAIaIQobChMI67fPtrqH4gIVVuDtCh05yApiEAAAYAiAAEgKP4vD_BwE.

SimaPro 9 (2019) <https://simapro.com/2019/> PréConsultants (www.pre.nl) (*An LCA tool for analyzing products following the ISO 14040 series Standards*).
 The Nature Conservancy (accessed 2019) "The carbon footprint calculator",
<https://carbonfund.org/calculate-your-footprint/>. (*An online tool to estimate your personal carbon footprint.*)

7.9 Exercises

E7.1. Data precision. If the values for CO₂ emissions used in the Alpure water case study in this chapter are uncertain by a factor of $\pm 20\%$, does the conclusion change? Mark approximate $\pm 20\%$ error margins onto the top of each bar in a copy of the audit for the Alpure bottle, Fig. 7.4 of the text (you are free to copy it), and then state your case.

E7.2. Combustion. More responsible consumers of Alpure water do not incinerate the empty bottles but send them instead to a waste-energy recovery plant where they are combusted under controlled conditions, capturing heat that is used to generate electrical energy. If the combustion efficiency is 24% (meaning that 24% of the heat of combustion of the PET is converted to useful electrical energy), what is the potential end-of-life energy credit per bottle? How does this compare with the embodied energy of the original, virgin PET bottle? Tables B2 and B8 have the necessary data.

E7.3. Recycling credits (1). Combustion with heat recovery recovers energy at end of life but releases carbon to the atmosphere. Recycling has the potential to conserve both energy and carbon. If 20% of all Alpure PET bottles (mass 0.4 kg/bottle) are recycled at end of life, what are the potential energy and carbon credits? Tables B2 and B7 have the necessary data.

E7.4. Recycling credits (2). The makers of Alpure wish to make their product more eco-friendly. They replace the virgin PET bottle with one of identical size, made of recycled polyethylene, and they charge a deposit on the bottle to ensure a high return rate and undertake to recycle all that are returned. How does this change the carbon fingerprint of the product? Retrieve the necessary data from Appendix B and mark the resulting changes onto a copy of Fig. 7.5.

E7.5. Material substitution. Alpure water has proved to be popular. The importers now wish to move upmarket. To do so they plan to market their water in 1-L glass bottles of appealing design instead of the rather ordinary PET bottles with which we are familiar. A single 1-L glass bottle weighs 430 g, much more than the 40 g of those made of PET. Critics argue that this marketing strategy is irresponsible because of the increased weight. The importers respond that glass has a lower embodied energy and carbon footprint than PET. Does the switch to glass really reduce the life carbon of

the bottle? Tables B2 and B6 contain the necessary data for the carbon footprint of glass and of glass molding.

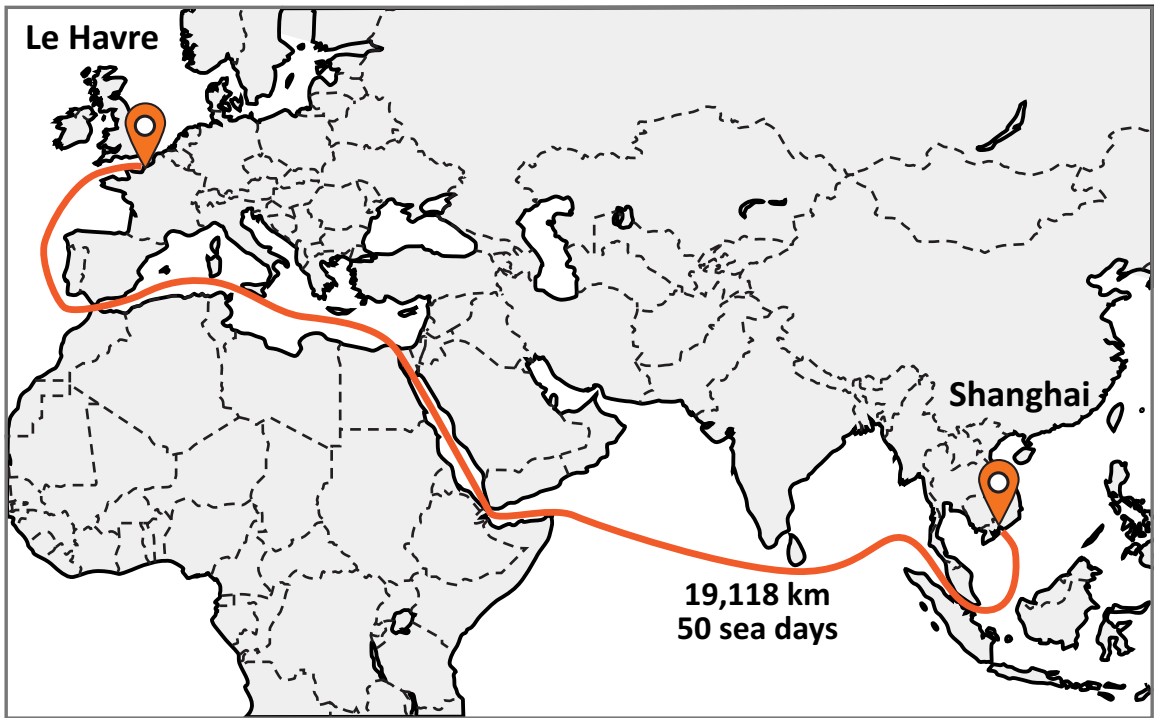
E7.6. Transport (1). A top London restaurant, we shall call it the Extravaganza, is impatient to receive its consignment of Alpure water in crafted glass bottles and decides to have a consignment airfreighted from France rather than wait for delivery by road. A single 1-L glass bottle weighs 430 g. Filled with water, the combined weight is 1.43 kg. What is the carbon footprint per bottle if transported by air? Table B9 has the necessary data. Use the Internet to find the distance from Zurich (the nearest airport to Evian) to London.

E7.7. Transport (2). Jug kettles have become an item of kitchen fashion. Amazon advertises more than 70 different models, and it is not unusual for makers to produce a new model every year. Many, like the one described in the text, are manufactured in China and transported to the United States and Europe. Shipping is slow; an upmarket appliance store will want the latest offerings on its shelves as quickly as possible. How much additional energy is consumed if the 0.8-kg kettle described in the text is airfreighted from Shanghai to Chicago? Use the Internet to find the air miles between the two cities and Table B9 to find the energy commitment of long-haul air freight.

E7.8. Transport (3). Plastic garden chairs are manufactured in China and shipped from Shanghai to the port of Le Havre, France, a distance of 19,118 km, for distribution around Europe. The chairs are made of molded polypropylene, weigh 4 kg, and are designed to be used (and left) outdoors. At the end of life they are sent, with other mixed plastic, to a waste-heat recovery plant where they are combusted with energy recovery at an efficiency of 25%.

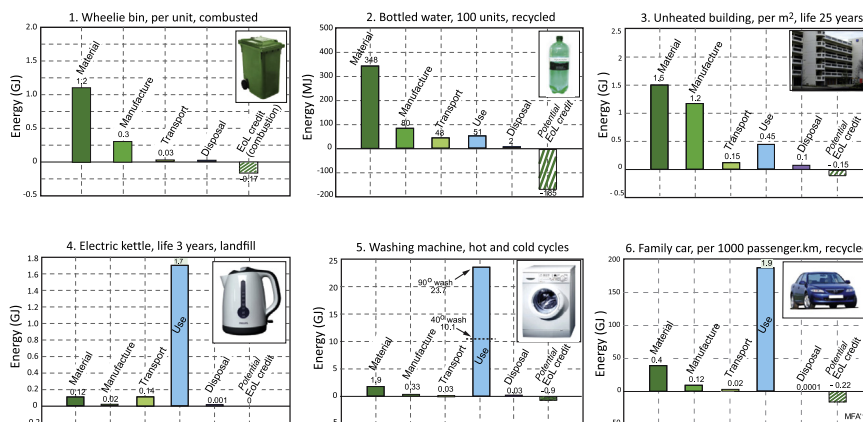


- (a) Create an energy fingerprint for the chair. The relevant data are contained in Tables B2, B6, B8, and B9.
- (b) Shanghai to Le Havre by ocean freight takes 50 sea days. The makers of the chairs are exploring faster delivery to France by the newly



connected rail link across Asia and Europe. Use the Internet to find the Shanghai–Paris distance and time by rail. Use the information to calculate the transport energy by this faster route. How does it compare with that of ocean freight?

Case studies: eco-audits



CONTENTS

- 8.1 Introduction and synopsis
- 8.2 A wheeley bin
- 8.3 Reusable and disposable cups
- 8.4 Carrier bags
- 8.5 A coffee maker
- 8.6 An A-rated washing machine
- 8.7 Ricoh Imagio MF6550 copier
- 8.8 A portable space heater
- 8.9 Auto bumpers: exploring substitution
- 8.10 Family car: comparing material energy with use energy
- 8.11 Computer-assisted audits: a hair dryer
- 8.12 Summary and conclusions
- 8.13 Exercises

8.1 Introduction and synopsis

The cover picture of this chapter shows *energy fingerprints* for a range of products. The products in the upper row are material intensive: a wheeled bin, bottled water, and an unheated building; for these, the embodied energy of the materials and manufacture dominate the breakdown. But this is unusual. The products in the second row are more typical; for all of these, it is the use phase that consumes more energy than all the others together. The carbon fingerprints look very similar.

This chapter describes eco-audits for 10 diverse products, using the methods of Chapter 7. Each section lists the bill of materials and processes, and suggests a transport route, a duty cycle, and an end-of-life choice. They illustrate the features of an eco-audit: it is fast and allows a “what if” exploration of changes in materials, process, transport, and use. But they are also approximate. Are they so approximate that they are meaningless? Comparison of eco-audits with more exhaustive analyses using life-cycle assessment (LCA) methods, described here, shows that eco-audits capture the important features of the energy and carbon emissions of a life cycle, or of part of a life cycle, well. They provide the tool we need to perform the first part of the strategy suggested in Chapter 7, Fig. 7.2.

Approximate values for the embodied energy of six products, showing the breakdown across the phases of life. The carbon footprints follow a similar pattern.

8.2 A wheelie bin

The bin shown in Fig. 8.1 is designed to meet European standard DIN-EN840 for the safety of both the refuse collector and the user. It is manufactured in Poland and imported by road to a distribution point in the United Kingdom, a distance of 1750 km, by 26-tonne (three-axle) truck. The bin is molded from high-density polyethylene (HDPE) with butyl-rubber wheels and weighs 15 kg. Its guaranteed life is 3 years, after which it could be recycled, but in practice it is combusted with energy recovery because of shortage of recycling capacity.¹ The bin uses no energy during its life. The necessary data, drawn from Appendix B, are assembled in Tables 8.1A–C.

Fig. 8.2 shows the energy and carbon fingerprints of the bin. Both are dominated, on the left, by the material. The contribution of transport is small. Combustion with heat recovery captures a little energy but is a disaster for carbon emissions: all the carbon of both polymers is released as CO₂.

8.3 Reusable and disposable cups

Disposable cups seem all wrong—fill them once, then throw them away. Would not reusable cups be more eco-benign? The answer is not as simple as it might seem. Reusable cups are more energy intensive to make and they have to be



FIGURE 8.1 *A wheelie bin.*

¹See newsclip at the end of Section 4.3, Chapter 4.

Table 8.1A The materials of the wheelie bin

Bill of materials			Material properties ^a	
Component	Recycled content ^a (%)	Part mass (kg)	Embodied energy (MJ/kg)	CO ₂ footprint (kg/kg)
HDPE body and wheels	0%	14.2	81	2.8
Steel axle and hinge	40%	0.6	22	1.7
Butyl-rubber tires	0%	0.2	95	4.4
Total mass		15		

^aAppendix B, Tables B2 and B7.

HDPE, high-density polyethylene.

Table 8.1B Transport mode, energy, and carbon footprint^a

Transport mode	Distance (km)	Mass (kg)	Energy (MJ/tonne · km)	CO ₂ footprint (kg CO _{2,eq} /tonne · km)
26-tonne (three-axle) truck	1750	15	1.1	0.085

^aAppendix B, Table B9.**Table 8.1C** Heat and carbon of combustion of materials^a

Material	Part mass (kg)	Heat of combustion (MJ/kg)	CO ₂ of combustion (kg/kg)
HDPE	14.2	81	2.8
Butyl rubber	0.2	95	4.4

^aAppendix B, Table B8.

HDPE, high-density polyethylene.

collected and washed in ways that meet health standards. They become a more energy-efficient choice only if reused a sufficiently large number of times.

Here we compare the energy profiles of 0.25 L disposable polystyrene cups with reusable polycarbonate cups of the same volume (Fig. 8.3), calculating the break-even number of reuse cycles. We take as the functional unit 1000 cups plus the associated cardboard packaging. Tables 8.2 and 8.3 list the attributes of the cups and of the virgin materials from which they are made (health requirements rule out recycled materials), taking the data from Appendix B. Transport requirements are negligible. It is assumed (wrongly) that the cups are recycled at end of life.

Washing 1000 polycarbonate cups once requires 20 kWh of electrical energy. To convert this to MJ_{oe} we first multiply by 3.6 to convert kWh to MJ, and then

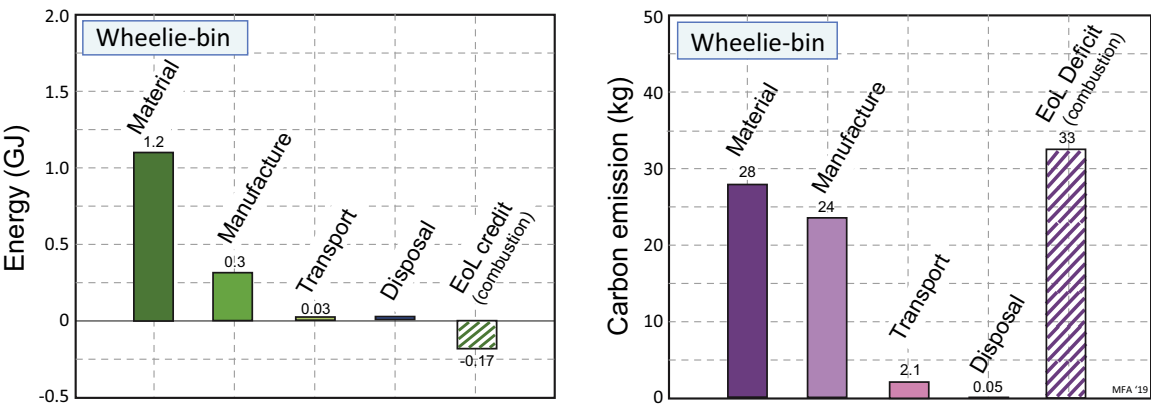


FIGURE 8.2 Energy and carbon fingerprints for the wheelie bin. EoL, end of life.



FIGURE 8.3 A disposable polystyrene cup and a reusable polycarbonate cup.

Table 8.2 Material, manufacture, and use of 1000 cups

Attribute	Disposable	Reusable
Material	Polystyrene	Polycarbonate
Mass of 1000 cups (kg)	16	113
Shaping process	Molding	Molding
Mass of cardboard packaging for 1000 cups (kg)	0.6	2.3

divide by the conversion efficiency from oil to electricity, which we set at the European average of 0.38, giving $E_{wash} = 195 \text{ MJ}_{oe}$, with a carbon release of $(\text{CO}_2)_{wash} = 13.7 \text{ kg}$ (Table B10(a)).

Table 8.3 Carbon footprint of materials and processes

Attribute	Polystyrene	Polycarbonate	Cardboard
Carbon footprint, virgin material CO _{2,eq} (kg/kg) ^a	2.7	5.6	1.4
Molding carbon footprint, CO _{2,eq} (kg/kg) ^a	1.3	1.3	-

^aFrom the data sheets of Appendix B, Tables B2 and B6.

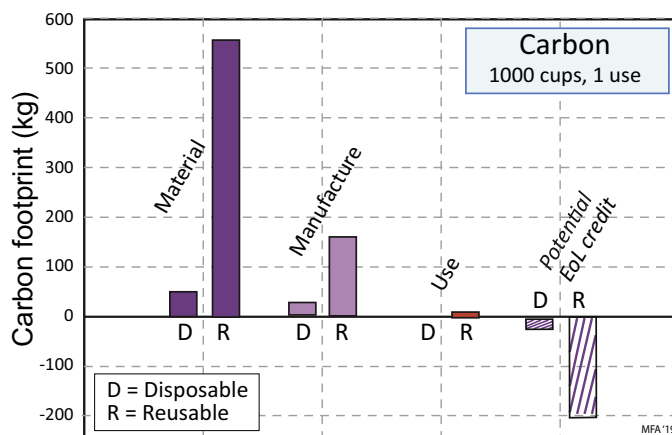


FIGURE 8.4 Comparison of a disposable polystyrene cup and a reusable polycarbonate cup, both used once. EoL, end of life.

Fig. 8.4 shows the carbon distribution per 1000 cups for a single use: the reusable cups emit far more than the disposable ones. They are, of course, designed to be used many times, which will increase the use energy without increasing the energy of manufacture. How many times before the reusables are more carbon efficient than the disposables?

The carbon of material and manufacture of 1000 disposable cups plus cardboard packaging is:

$$(\text{CO}_2)_{\text{Disposable}} = 16 \times (2.7 + 1.3) + 0.6 \times 1.4 = 65 \text{ kg}$$

That for 1000 reusable cups is:

$$(\text{CO}_2)_{\text{Reusable}} = 113 \times (5.6 + 1.3) + 2.3 \times 1.4 = 783 \text{ MJ}$$

Suppose the reusable cups are used, on average, n times. Then they become more energy efficient when:

$$n(\text{CO}_2)_{\text{Disposable}} > (\text{CO}_2)_{\text{Reusable}} + (n - 1)(\text{CO}_2)_{\text{Wash}}$$

Inserting the data and solving for n reveals that reusable cups are more carbon efficient only if reused at least 15 times.

This might be an achievable target in a restaurant, but for outdoor events it is totally unrealistic. Garrido and del Castillo, investigating a major outdoor event at the Barcelona Universal Forum of Culture in 2004, report the gloomy statistic that only 20% of reusable cups were actually returned. The rest ended up in waste or simply disappeared.

Further reading

Garrido, N. and del Castillo, M.D.A. (2007) “Environmental evaluation of single-use and reusable cups”, *Int. J. LCA*, vol. 12, pp. 252–256.

Imhoff, D. (2005) “Paper or plastic: searching for solutions to an overpackaged world”, University of California Press. (*What the title says: a study of packaging, taking a critical stance.*)

8.4 Carrier bags

Few products get a worse press than plastic carrier bags. They are (or were) distributed free, and in vast numbers.² They are made from oil. They don’t degrade. They litter the countryside and the oceans, snaring waterbirds and choking turtles. Add your own gripe.

Paper bags are made from natural materials, and they bio-degrade. Surely it’s better to use paper? And come to think of it, why not bags made out of jute? It’s a renewable resource and it’s tough enough to last for a long time.

Fig. 8.5 shows real bags. Bag 1 is a typical single-use supermarket container. It is made of polyethylene (PE) and it weighs just 7 g. Bag 2 is also PE but it is three times heavier and the designer graphics tell you something else: the bag is a statement of the cultural and intellectual standing of the store from which it comes (it is a bookshop). It is attractive and strong, too good to throw away, at least not straightaway.

Bags 3 and 4 are made of paper. Paper bags suggest a concern for the environment, a deliberate avoidance of plastic, good for company image. But there is more mass of material here—about seven times more than that of bag 1.

And finally, reusable bags—“bags for life,” as one supermarket calls them. Bag 5 is an example. It is robust and durable and looks and feels as if made from a woven fabric, but it’s not—it’s textured polypropylene sheet. The color, the “Saving Australia” logo, and the sense that it really *is* green propelled this bag into near-universal popularity there. Here is one Aussie paper: “Forget the little black dress. The hot new item around town is the little green bag.”

But isn’t “saving the planet” a little bit, well, yesterday? Today is bag 6. Discrete, understated, almost (but not quite) unnoticeable. People who have one

²In the period between the second edition (2013) and the present edition (2020) of this book, many nations have banned single-use plastic bags.



FIGURE 8.5 Carrier bags. The lightest weighs 7 g, the heaviest weighs 257 g.

have the quiet satisfaction of knowing that it is made of *Juco*, a mix of 75% jute and 25% cotton, natural, renewable, and compostable. We have wandered here into a world that is not just about containment; it is also about company branding and self-image.

Our interest is eco-analysis, not psychoanalysis. So consider the following question. If the 7-g plastic bags are really used only once, how many times do you have to use the others to do better in eco-terms? [Table 8.4](#) lists the necessary data: the mass of each bag, the carbon footprint of the bag materials, and the carbon release per bag. The last column of [Table 8.4](#) list the number of times the others must be used to provide containment at lower carbon release than bag 1. If the bags are incinerated at end of life, releasing the carbon locked up in their materials, the numbers become even more extreme.

Table 8.4 The characteristics of the carrier bags shown in Fig. 8.4					
Bag	Material	Mass (g)	Material CO ₂ footprint (MJ/kg) ^a	CO ₂ footprint, 100 bags (kg)	How many reuses?
1	Polyethylene	7	1.9	1.3	1
2	Polyethylene	20	1.9	3.8	3
3	Paper, unglazed	46	1.2	5.5	5
4	Paper, glazed	54	1.2	6.5	5
5	Polypropylene	75	2.9	22	17
6	Juco —75% Jute 25% cotton ³	257	0.57	15	12

^aFrom Appendix B, Table B2.

Now you must make a judgment. Would you reuse a paper bag five or more times? Unlikely—they tear easily and get soggy when wet. Would you use the green bag 5 more than 17 times or the jute bag more than 12? I have examples of both and both have already been used more than that, so they look like potential winners provided nothing leaks or breaks inside them, causing terminal contamination.

So, from a carbon and energy point of view, single-use bags are not necessarily bad; it depends how meticulous you are about reusing any of the others. The real problem with plastic sheet is its negligible value (so people discard it without thought) and its long life, causing it to accumulate on land, in rivers, and in the seas.

Further reading

Edwards, C. and Fry, J.M. (2011, accessed 2019) “Life-cycle assessment of supermarket carrier bags”, Report: SC030148, The Environment Agency, Bristol, BS1 5AH, UK. http://www.designingourtomorrow.com/business/UND_energy_quiz/Carrier_Bags_Report_EA.pdf (*An example of LCA at its most LCA-like.*)

González-García, S., Hospido, A., Feijoo, G., and Moreira, M.T. (2010) “Life cycle assessment of raw materials for non-wood pulp mills: Hemp and flax Resources”, *Conservation and Recycling*, vol. 54, pp. 923–930.

Imhoff, D. (2005) “Paper or plastic: searching for solutions to an overpackaged world”, University of California Press. (*A study of packaging taking a critical stance.*)

³Singh, A.K., Kumar, M., Mitra, S. “Carbon footprint and energy use in jute production,” *Indian Journal of Agricultural Sciences*, 88(8): 1305–1311 (2018).

Shen L. and Patel, M.K. (2008) "Life cycle assessment of polysaccharide materials: a review", J. Polymer Environ., vol.16, pp. 154–167. (*A survey of the embodied energy and emissions natural fibers.*)

8.5 A coffee maker

A 640-W coffee maker (Fig. 8.6) makes four cups of coffee in 5 minutes (requiring full power) and then keeps the coffee hot for a subsequent 30 minutes, consuming one-sixth of full power. It is manufactured in Southeast Asia and shipped 19,000 km to Europe, where it is sold and used. At the end of life, it is sent to landfill.



FIGURE 8.6 A coffee maker.

Table 8.5 summarizes the bill of materials. The housing is injection-molded polypropylene, the jug is glass, and there are a number of small steel and aluminum parts, a heating element, and a cable and plug. The control system has some simple electronics and an LED indicator. Each brew requires a filter paper that is subsequently discarded. We take the life of the coffee maker to be 5 years, over which time it is used once per day.

Table 8.5 Coffee maker, life 5 years

Bill of materials and processes				Material and process properties ^a			
Component	Material	Process	Mass (kg)	Material energy (MJ/kg)	Process energy (MJ/kg)	Material CO ₂ (kg/kg)	Process CO ₂ (kg/kg)
Housing	Polypropylene	Molding	0.91	80	20.5	2.9	1.3
Small steel parts	Steel	Rolling	0.12	31	4.5	2.5	0.3
Small aluminum parts	Aluminum	Rolling	0.08	190	4.5	12	0.3
Glass jug	Glass (Pyrex)	Molding	0.33	29	9.5	1.7	0.6
Heating element	Ni—Cr alloy	Wire drawing	0.026	220	35	12	2.3
Electronics and LED	Electronics	Assembled	0.007	1800	-	130	-
Cable sheath, 1 m	Poly(vinyl chloride)	Extrusion	0.12	65	6.5	2.7	0.4
Cable core, 1 m	Copper	Wire drawing	0.035	59	35	3.6	2.3
Plug body	Phenolic	Molding	0.037	77	20.5	1.9	1.3
Plug pins	Brass	Extrusion	0.03	72	14	6.3	0.9
Packaging, padding	Polymer foam	Molding	0.015	80	20.5	5.1	1.3
Packaging, box	Cardboard	Construction	0.125	28	-	0.71	-
Other components	Proxy material: polycarbonate	Proxy process: molding	0.04	110	20.5	4.8	1.3
Total mass			1.9				

^aFrom Appendix B, Tables B2 and B6.

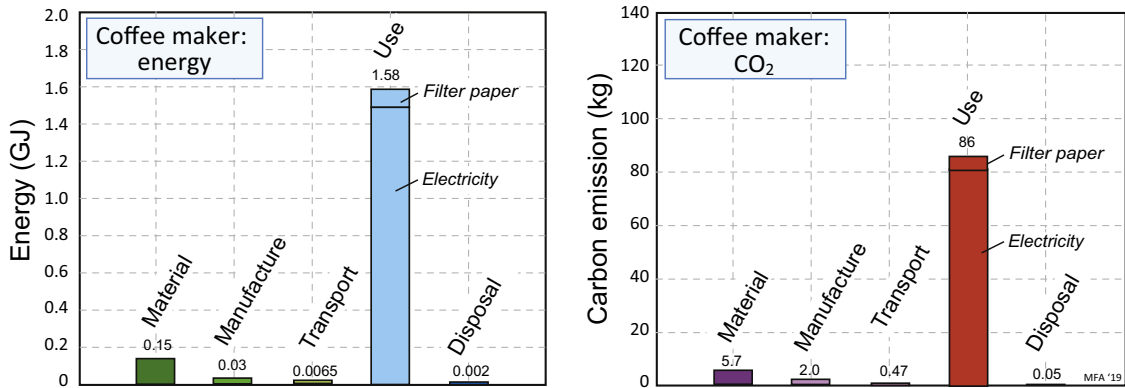


FIGURE 8.7 *The energy and carbon fingerprints of the coffee maker.*

Transport by ocean shipping (Table B9) consumes 0.18 MJ/tonne·km and releases 0.013 kg of CO_{2,eq}/tonne·km. A single use cycle uses the equivalent of 10 minutes of full 640 W power. Over 5 years this consumes 194 kWh of electrical power, which, if generated in the United States (Table B11), corresponds to an equivalent oil consumption of 1570 MJ and CO₂ emission of 97 kg of CO₂. Each use also consumes one filter paper—1825 of them over life—each weighing 2 g, making 3.65 kg of paper. The average embodied energy of paper is 28 MJ/kg, with an associated emission of 0.7 kg/kg CO₂, so the filter papers add 102 MJ to the use energy and 2.6 kg to the use carbon.

Fig. 8.7 shows the resulting energy and carbon fingerprints. The first three bars—materials, manufacture, and transport—are all small compared with the energy and carbon of use. There is nothing that can be done to recover the electrical power once it is used, but it *is* possible to reduce it by a factor of 2 by replacing the glass jug with a stainless steel vacuum jug, thereby eliminating the need for a heater to keep the coffee warm. The embodied energy of stainless steel is three times greater than that of glass, so it is necessary to check that this redesign really does save energy over life—a task left to the exercises at the end of this chapter.

8.6 An A-rated washing machine

Household appliances like washing machines (Fig. 8.8) are major consumers of energy. On average, a washing machine is used for 220 wash cycles per year and lasts for 10 years. The energy it consumes depends on the wash temperature, on whether it is hot-filled or cold-filled, and on the choice of cycle: an A-rated machine requires 1.22 kWh for a 90°C wash and 0.56 kWh for a 40°C wash, averaging out at 0.85 kWh for a typical mix between washes (National Energy Foundation, 2011). For illustration we assume that the washing machine is manufactured in



FIGURE 8.8 *A washing machine.*

Germany and delivered to the United Kingdom, a distance of 1000 km, by 40-tonne (six-axle) truck. At end of life it is shredded, recovering the metallic materials, roughly 49% of the total weight. The left side of Table 8.6 lists the bill of materials for a washing machine, taken from the study by Stahel (1992). The eco-audit is based on this bill of materials, using the data shown on the right of Table 8.6.

Fig. 8.9 shows the results, using the average wash-mix cycle energy of 0.85 kWh. The use phase outweighs all others by a factor of at least 6. The recycling of metals at end of life allows about a third of the material energy to be recovered. The transport of the washing machine over 1000 km makes negligible difference to the totals.

Further reading

National Energy Foundation (2011) www.nef.org.uk/energysaving/labels.htm (*Use energy for A- to E-rated washing machines.*)

Washing machine (2011) ETH Sustainability Summer School report, http://webarchiv.ethz.ch/sustainability-v2/lehre/Sommerakademien/so2011/washies_report.pdf

8.7 Ricoh Imagio MF6550 copier

Ricoh provides environmental product declarations (EPDs) for its products. That for their MF6550 digital copier (Fig. 8.10) includes an approximate bill of materials, shown on the left of Table 8.7. The typical service life of the copier is 5 years, during which time it is used 8 hours per day for 20 days per month, consuming, on average, 0.35 kW of electrical power over that time. During its life, the copier consumes 2,880,000 sheets of paper weighing 12,215 kg. At end of life, 85% of copiers are returned to Ricoh, where they are recycled, recovering 95% of the material content. The residue goes to landfill. Transport was set at 200 km by 14-tonne truck for initial delivery plus 800 km by light goods vehicle for four annual services.

Table 8.6 The washing machine, life 10 years

Bill of materials			Material properties ^a	
Component	Recycled content (%)	Part mass (kg)	Embodied energy (MJ/kg)	CO ₂ footprint (kg/kg)
Mild steel parts	42%	23	22	1.7
Cast iron parts	69%	3.8	8.9	0.5
HSLA steel parts	Virgin (0%)	6.2	31	2.5
Stainless steel parts	38%	5.4	59	3.7
Aluminum parts	43%	1.9	134	7.6
Copper, brass parts	43%	1.8	48	3.5
Zinc parts	Virgin (0%)	0.1	52	4.0
Polystyrene parts	Virgin (0%)	2.1	82	2.5
Polyolefin parts (polypropylenes)	Virgin (0%)	1.3	80	2.9
Poly(vinyl chloride) parts	Virgin (0%)	0.7	65	2.7
Nylon parts	Virgin (0%)	0.4	140	7.0
Other polymers (ABS)	Virgin (0%)	1.9	92	3.4
Rubber parts	Virgin (0%)	1.6	78	2
Concrete blocks ^b	Virgin (0%)	22	0.82	0.12
Cardboard packaging	Virgin (0%)	2.3	28	0.7
Wood parts	Virgin (0%)	2.5	11	0.37
Borosilicate glass	Virgin (0%)	0.1	29	1.7
Total mass		77		

^aFrom Appendix B, Tables B2 and B7.

^bThe 22 kg of concrete suppresses vibration during the spin cycle.
 ABS, acrylonitrile butadiene styrene; HSLA, high-strength, low-alloy.

The bar chart of Fig. 8.11 shows the output of the eco-audit with the use phase split into two parts, one for the electrical energy, the other for the paper. The eco-audit matches the EPD well in energy of material and manufacture, in use of electric power, and in the strikingly large energy associated with paper. Ricoh points out that double-sided copying or, better, double sided with two pages on each face, is the obvious way to save energy.

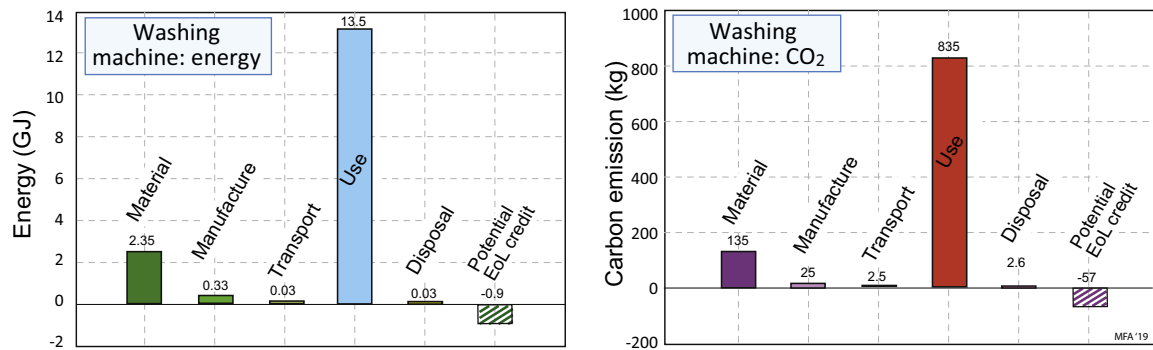


FIGURE 8.9 The energy and carbon footprint of an A-rated washing machine, based on data from Stahel (1992) and the National Energy Foundation (2011). EoL, end of life.



FIGURE 8.10 A Ricoh Imagio MF6550 copier.

Further reading

Ricoh (2010) “Environmental Product Declaration for the Ricoh imagio MF6550 digital copier”, <http://www.ricoh.com>.
Ricoh Group Integrated Report (2018), https://www.ricoh.com/-/Media/Ricoh/Sites/com/sustainability/report/download/pdf2018/all_E.pdf

8.8 A portable space heater

The space heater shown in Fig. 8.12 is carried as part of the equipment of a light goods vehicle used for railway repair work. It has a 3-year life. It burns 0.66 kg of liquid propane gas (LPG) per hour, delivering an output of 9.3 kW (32,000 Btu)

Table 8.7 The copier (paraphrased from Ricoh, 2010), life 5 years

Bill of materials			Material properties ^a	
Component	Recycled content ^a (%)	Part mass (kg)	Embodied energy (MJ/kg)	CO ₂ footprint (kg/kg)
Steel press parts	42%	110	22	1.7
Zinc parts	22%	3.7	44	3.4
Copper/brass parts	43%	1.5	39	2.5
Polystyrene parts	0%	8.5	82	2.5
ABS parts	0%	4	92	3.4
PC parts	0%	2.4	110	4.8
POM parts	0%	1.4	86	3.2
Polypropylene parts	0%	1.1	80	2.9
PET parts	0%	0.8	82	2.7
Glass parts	0%	2.2	11	0.76
Neoprene parts	0%	5	64	1.5
Paper	50%	12,215	22	0.7
Other materials (PC proxy)	0%	15	110	4.8
Total mass		180		

^aAppendix B, Tables B2 and B7

ABS, acrylonitrile butadiene styrene; PC, polycarbonate; PET, polyethylene terephthalate; POM, polyoxymethylene.

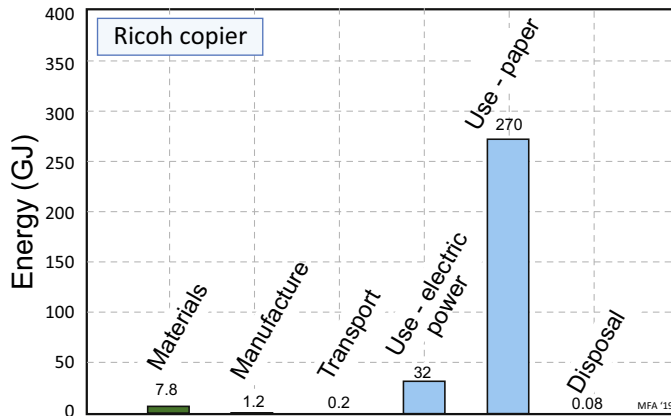
**FIGURE 8.11** The energy audit for the Ricoh copier. The contribution of the paper dominates.



FIGURE 8.12 *A space heater powered by liquid propane gas.*

and releasing 3.03 kg of CO₂ for every kilogram of LPG that is burned (Appendix B, Table B10(a)). The airflow is driven by a 38-W electric fan. The heater weighs 7 kg. The (approximate) bill of materials is listed in Table 8.8. The product is manufactured in India and shipped to the United States by sea freight (14,400 km) and then carried by 32-tonne truck for a further 1600 km to the point of sale. It is anticipated that the light goods vehicle carrying it will travel, on average, 550 km per week, over a 3-year life, releasing 0.17 kg CO₂/tonne km (Table B9). The heater itself will be used for 2 hours per day for 10 days per year. At end of life the carbon steel components are recycled.

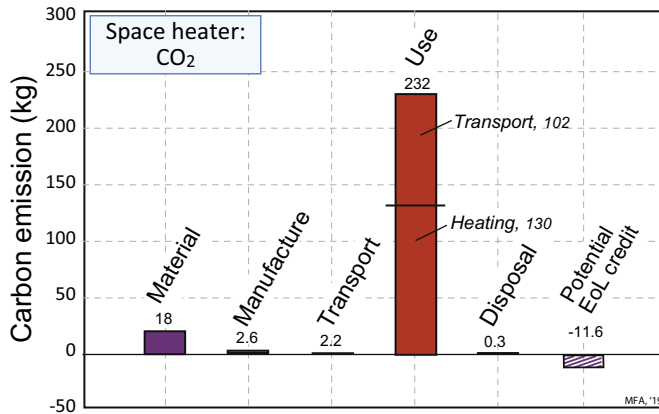
This is a product that uses energy during its life in two distinct ways. First there is the electricity and LPG consumed in its role as a heater. Second there is the energy penalty that arises because it increases the weight of the vehicle that carries it by 7 kg. How much CO₂ is the product responsible for over its 3-year life? And which part of the life is responsible for the most?

Fig. 8.13 shows the CO₂ emission profile. The first two bars—materials (18.1 kg) and manufacture (2.6 kg)—are calculated from the data in the table. Transport by ocean freight releases 0.014 kg CO₂/tonne·km (Table B9), so shipping releases only 1.4 kg CO₂ per unit; trucking adds another 0.8 kg. The power consumed by burning LPG for heat (9.3 kW) far outweighs that used to drive the small electric fan motor (38 W), so it is the CO₂ released by burning LPG that we need (Table B10): it is 120 kg over the 3-year life. It is less obvious how the static use for generating heat, drawn for only 20 hours per year, compares with the extra fuel consumed by the vehicle because of the product weight—remembering that, as part of the equipment, it is lugged over 28,000 km per year, releasing 102 kg of CO₂ over the 3-year life.

The figure shows that the CO₂ of use outweighs all other contributions (as it does with most energy-using products), here accounting for 93% of the total. Of this, about half derives from burning gas and half from the additional fuel consumed by carrying

Table 8.8 Liquid propane gas space heater, life 3 years

Bill of materials and processes				Material properties ^a	
Component	Material	Process	Mass (kg)	Material CO ₂ (kg/kg)	Process CO ₂ (kg/kg)
Heater casing	Low-C steel	Roll forming	5.4	2.3	0.3
Fan	Low-C steel	Roll forming	0.25	2.3	0.3
Heat shield	Stainless steel	Roll forming	0.4	5.4	0.3
Motor, rotor, and stator	Iron	Roll forming	0.13	2.4	0.3
Motor, conductors	Copper	Wire drawing	0.08	3.6	2.3
Motor, insulation	Polyethylene	Polymer extrusion	0.08	2.9	0.42
Connecting hose, 2 m	Natural rubber	Polymer extrusion	0.35	2.0	0.42
Hose connector	Brass	Casting	0.09	3.6	0.65
Other components	Proxy material: polycarbonate	Proxy process: polymer molding	0.22	4.8	1.3
Total mass			7.0		

^aAppendix B, Tables B2 and B6.**FIGURE 8.13** The energy breakdown for the space heater. The use phase dominates. EoL, end of life.

the heater to the sites where it is used. The CO₂ burden to recycle steel, from Appendix B, Table B7, is about 0.65 kg/kg, potentially saving the difference between this and that for primary production (2.3 kg/kg)—a net savings of 11.6 kg.

8.9 Auto bumpers: exploring substitution

Car bumpers (Fig. 8.14) are heavy. Reducing their mass can save fuel. Here we explore the replacement of a low-carbon steel bumper with one of equal performance made of an age-hardening aluminum or of carbon-fiber-reinforced polymer (CFRP). The steel bumper weighs 14 kg; the aluminum substitute weighs 11 kg, the CFRP substitute only 8 kg. But the embodied energies of aluminum and of CFRP are much higher than that of steel. Is there a net savings? We examine a gasoline-powered vehicle with a life of 10 years, driven 25,000 km per year. Table 8.9 lists the energies involved. The energy penalty of weight for a gasoline-powered car is 2.6 MJ/tonne · km (Appendix B, Table B9).

Table 8.9 compares the material energy, the use energy, and the sum of the two, assuming the use of virgin material for both the steel and the aluminum bumper. The substitution of steel by either aluminum or CFRP results in a large increase in material energy but a decrease in use energy. The last column shows the sum of the two: the aluminum bumper has a lower total energy than the steel, but not by much—the break-even comes at about 200,000 km. The CFRP substitute reduces the life energy a little more, despite its high embodied energy. Both aluminum and CFRP cost more than steel. A final decision needs a cost–benefit trade-off. Methods for doing that come in the next chapter.

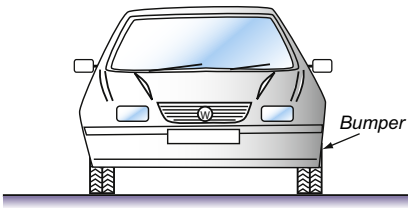


FIGURE 8.14 Car and bumper.

Table 8.9 The analysis of the material substitution					
Material and mass		Material properties	Eco-audit of bumper		
Material of bumper	Mass (kg)	Embodied energy (MJ/kg) ^a	Material energy (MJ)	Use energy (MJ)	Total: Material plus use (MJ)
Low-carbon steel	14	31	432	9100	9530
Age-hardened aluminum	11	190	2090	7150	9240
CFRP	8	480	3840	5200	9040

^aAppendix B, Tables B2 and B9.
CFRP, carbon-fiber-reinforced polymer.

But this comparison has not been quite fair. A product like the bumper would incorporate recycled as well as virgin material. It is possible, using the data given in the data sheets of Appendix B, to correct the material energies for the recycled content. This is left to the exercises at the end of this chapter.

8.10 Family car: comparing material energy with use energy

Argonne National Laboratory, working with the US Department of Energy, has developed a model (GREET) to evaluate energy and emissions associated with vehicle life. Table 8.10 lists the bill of materials for two of the vehicles they analyze: a conventional steel-bodied midsize family car with internal combustion engine and a vehicle of similar size made of lightweight materials, principally aluminum and CFRP. The biggest differences in data values are italicized and in bold. The total mass is shown at the bottom of the columns. Lightweighting reduces it by 39%.

Appendix B provides the embodied energies of the materials. Fuel consumption scales with weight in ways that are analyzed in Chapter 6; for now we use the results that a conventional car of this weight consumes 3.15 MJ/km, the lighter one consumes 2.0 MJ/km.⁴ There is enough information here to allow an approximate comparison of embodied energy and the use of the two vehicles, assuming both are driven 25,000 km per year for 10 years.

The bar charts of Fig. 8.15 show the comparison. The input data are of the most approximate nature, but it would take very large discrepancies to change the conclusion: the energy consumed in the use phase of both vehicles greatly exceeds that embodied in their materials. The use of lightweight materials increases the embodied energy by 38% but reduces the much larger fuel-energy consumption by 37%. The result is a net gain: the sum of the material and use energies for the lightweight vehicle is 31% less than that of the conventional one.

Further reading

Burnham, A., Wang, M. and Wu, Y. (2006), "Development and applications of GREET 2.7", ANL/ESD/06-5, Argonne National Laboratory, Argonne, Ill. USA, www.osti.gov/bridge. (*A report describing the model developed by ANL for the US Department of Energy to analyze life emissions from vehicles.*)

8.11 Computer-assisted audits: a hair dryer

Audits of energy and emissions are greatly simplified by the use of computer-based tools, one of which was described at the end of Chapter 7. As an example of its use,

⁴1 MJ/km = 2.86 L/100 km = 95.5 miles per UK gallon = 79.5 miles per US gallon.

Table 8.10 Material content of a conventional family car and one made of lightweight materials

Material	Material energy H_m (MJ/kg) ^a	Conventional ICE vehicle (kg)	Lightweight ICE vehicle (kg)
Carbon steel	31	839	254
Stainless steel	73	0.0	5.8
Cast iron	20	151	31
Wrought aluminum (10% recycled content)	174	30	53
Cast aluminum (35% recycled content)	135	64	118
Copper/brass	59	26	45
Magnesium	320	0.3	3.3
Glass	11	39	33
Thermoplastic polymers (PU)	82	94	65
Thermosetting polymers (polyester)	71	55	41
Rubber	95	33	17
CFRP	480	0.0	134
GFRP	120	0.0	20
Platinum, catalyst (Table B3)	290,000	0.007	0.003
Electronics, emission control, etc. (Table B4)	3000	0.27	0.167
Other (proxy material: polycarbonate)	110	26	18
Total mass		1361	836

^aAppendix B, Tables B2, B3, B4 and B7.

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer; ICE, internal combustion engine; PU, polyurethane.

consider one further case study: an eco-audit of a 2000-W electric hair dryer (Fig. 8.16). It is made in Southeast Asia and shipped by sea to Europe, roughly 20,000 km. The bill of materials and processes as entered into the tool is reproduced in Table 8.11. The dryer has an expected life of 3 years (it is guaranteed for only 2) and will be used, on average, for 3 minutes per day for 150 days per year. At end of life the polymeric housing and nozzle subsystem are recycled. The rest is dumped.

Fig. 8.17 and Table 8.12 show part of the output. The tool provides more detail: tables listing the energy and CO₂ emission that can be attributed to each component, and the details of the transport and use-phase calculations.

As with many other energy-using products, it is the use phase that dominates the audit. It may be possible to reduce the material bar of Fig. 8.17 a little by

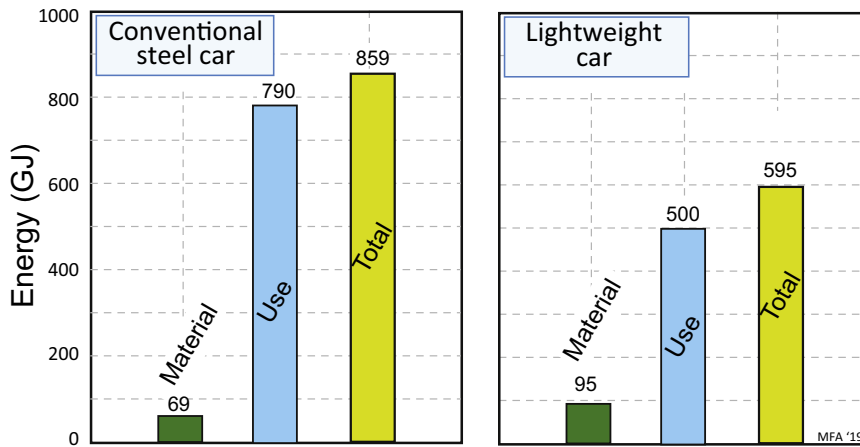


FIGURE 8.15 The comparison of the energy audits of the conventional and the lightweight family car.



FIGURE 8.16 A 2000-W “ionic” diffuser hair dryer.

substitution with less energy-intensive materials or by using a greater recycled content, but the effect of this on the life energy will be small. So the target has to be the heater. In the operation of a hair dryer, most of the heat goes straight

Table 8.11 The hair dryer, life 3 years

Bill of materials and processes				
Subsystem	Component	Material	Shaping process	Mass (kg)
Housing and nozzle	Housing	ABS	Polymer molding	0.177
	Inner air duct	Nylons (PA)	Polymer molding	0.081
	Filter	Polypropylene	Polymer molding	0.011
	Diffuser	Polypropylene	Polymer molding	0.084
Fan and motor	Fan	Polypropylene	Polymer molding	0.007
	Casing	Polycarbonate	Polymer molding	0.042
	Motor—iron	Low-carbon steel	Def. processing	0.045
	Motor—windings	Copper	Def. processing	0.006
	Motor—magnet	Nickel	Def. processing	0.022
Heater	Heating filament	Nickel—chrome alloys	Def. processing	0.008
	Insulation	Alumina	Ceramic power forming	0.020
	Support	Low-carbon steel	Def. processing	0.006
Circuit board and wiring	Board	Phenolics	Polymer molding	0.007
	Conductors	Copper	Def. processing	0.006
	Insulators	Phenolics	Polymer molding	0.012
	Cable sheathing	Poly(vinyl chloride)	Polymer molding	0.005
Cable and plug	Main cable, core	Copper	Def. processing	0.035
	Cable sleeve	Poly(vinyl chloride)	Polymer molding	0.109
	Plug body	Phenolics	Polymer molding	0.021
	Plug pins	Brass	Def. processing	0.023
Packaging	Rigid foam padding	Rigid polymer foam	Polymer molding	0.011
	Box	Paper and cardboard	Construction	0.141
Residual components	Residual components	Proxy material: polycarbonate	Proxy process: polymer molding	0.010
Total mass				0.89

ABS, acrylonitrile butadiene styrene; PA, polyamide.

past the head. The fraction that is functionally useful is not known, but it is small. Anything that increases this fraction contributes to energy efficiency. The diffuser (a standard accessory) does that, but a lot of hot air is still lost.

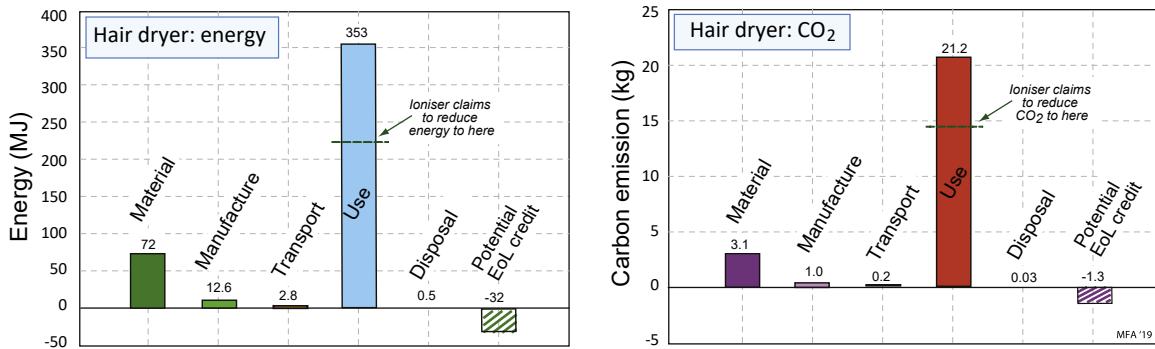


FIGURE 8.17 The energy and carbon fingerprint of the hair dryer. EoL, end of life.

Table 8.12 The energy and CO₂ breakdown for the hair dryer

Phase of life	Energy (MJ)	CO ₂ (kg)
Material	72.2	3.1
Manufacture	12.6	1.0
Transport	2.8	0.2
Use	353	21.2
Disposal	0.5	0.03
Total, end of first life	441	25.2
End-of-life potential	-32	-1.3

The makers of this hair dryer claim a dramatic development. Incorporated within it is a gas-discharge ionizer. It ionizes the air flowing past it, which, it is speculated, breaks down the water in the hair into smaller droplets, allowing them to evaporate faster. The manufacturers of ionic hair dryers claim that this dries the hair “twice as fast as non-ionic hair dryers” (it is printed on the box). If true, it gives an impressive total life-energy reduction of nearly 40%—it is marked on the figure. Although I have found no scientific basis for the claim, customer reviews express a preference for ionic hair dryers, so maybe it is real.

8.12 Summary and conclusions

What do these case studies tell us? For energy-using products (household appliances, cars, copiers), it is the use phase that dominates, frequently consuming more energy and creating more emissions than all the other phases combined. For products that

do not use energy or use very little (the wheeled bin, the disposable cups, the carrier bags), it is the embodied energy and associated CO₂ of the materials that dominate.

Eco-aware product design has many aspects, one of which is the choice of materials. Materials are energy intensive, with high embodied energies and associated carbon footprints. Seeking to use low-energy materials might appear to be one way forward, but this can be misleading. Material choice has consequences for manufacturing; it influences weight, thermal performance, and electrical characteristics. All change the energy consumed by the product during use and the potential for recycling or energy recovery at the end of life. It is full-life energy that we seek to minimize.

Doing so requires a two-part strategy developed in Chapter 3. The first part is an *eco-audit*: a quick, approximate assessment of the distribution of energy demand and carbon emission over life. This provides inputs to guide the second part: that of material selection to minimize the energy and carbon over the full life, balancing the influences of the choice over each phase of life—the subject of Chapters 9 and 10. The eco-audit method described here is fast and easy to perform, and although approximate, it delivers information with sufficient precision to enable strategic decision-making. The exercises that follow provide opportunities for exploring them further.

8.13 Exercises

E8.1. Redesign. If the glass container (weight 0.33 kg) of the coffee maker, audited in [Section 8.5](#) of the text, is replaced by a double-walled stainless steel one weighing twice as much, how much does the total embodied energy of the product change? If the replacement reduces the electric power consumed over life (1480 MJ) by 10%, does the energy balance favor the substitution?

E8.2. Making an eco-audit (1): irons. The figure shows a 1700-W steam iron. It weighs 1.3 kg, 98% of which is accounted for by the 7 components listed in the table. The iron heats up on full power in 4 minutes, is then used, typically, for 20 minutes on half power. At end of life the iron is dumped as landfill. Create an eco-audit for the iron assuming that it is used once per week over a life of 5 years, using data from the table below. Neglect transport and end of life.



What conclusions can you draw? How might the life energy be reduced?

Steam iron: bill of materials

Component	Material	Shaping process	Mass (kg)	Material energy ^a (MJ/kg)	Process energy ^a (MJ/kg)
Body	Polypropylene	Molded	0.15	80	6.5
Heating element	Nichrome	Wire drawn	0.03	220	35
Base	Stainless steel	Cast	0.80	73	9
Cable sheath	Polyurethane	Extruded	0.18	82	6.5
Cable core	Copper	Wire drawn	0.05	59	35
Plug body	Phenolic	Molded	0.037	77	20.5
Plug pins	Brass	Rolled	0.03	59	4.5
Total mass		1.28			

^aFrom Tables B2 and B6.

E8.3. Making an eco-audit (2): toasters. The figure shows a 970-W toaster. It weighs 1.2 kg, including 0.75 m of cable and plug. Its external surface (area 0.09 m²) has a baked-enamel coating. It takes 2 minutes 15 seconds to toast a pair of slices. It is used to toast, on average, eight slices per day, so it draws its full electrical power for 9 minutes (0.15 hours) per day for 300 days per year over its design life of 3 years. The toasters are made locally; transport energy and CO₂ are negligible. At end of life it is sent to landfill. Create an eco-audit for the toaster using data in the following table.



What conclusions can you draw? How might the life energy be reduced?

Toaster: bill of materials

Component	Material	Shaping process	Mass (kg)	Material energy ^a (MJ/kg)	Process energy ^a (MJ/kg)
Body	Polypropylene	Molded	0.24	80	20.5
Heating element	Nichrome	Drawn	0.03	220	35
Inner frame	Low-carbon steel	Rolled	0.93	31	4.5
Cable sheath	Polyurethane	Molded	0.045	82	6.5
Cable core	Copper	Drawn	0.011	59	35
Plug body	Phenolic	Molded	0.037	77	20.5
Plug pins	Brass	Rolled	0.03	70	4.5
Total mass		1.32			

^aFrom Appendix B, Tables B2 and B6.
The process energy for baked coatings (Appendix B, Table B6) is 65 MJ/m².

E8.4. Change of material: car bumpers. It is proposed to replace the low-carbon steel bumper set of Case Study 8.9 in the text by a set made of glass-fiber-reinforced polymer (GFRP). It is anticipated that the GFRP set will weigh 9.5 kg. Estimate whether, over a life of 250,000 km at an energy penalty of 2.6 MJ/tonne·km, the GFRP bumper set is more energy efficient than the equivalent steel or aluminum set described in the text if each has 50% recycled content. Would one choice be significantly better if the embodied energy data were in error by 10%? Data for virgin and recycled steel and aluminum are listed in Appendix B, Tables B2 and B7.

E8.5. Making an eco-audit (3): small car. The production of a small gasoline-powered car (mass 1000 kg) requires materials with a total embodied energy of 70 GJ and a further 25 GJ for the manufacturing phase. The car is manufactured in Germany, shipped by very large container ship from Bremen to New York (6460 km), and delivered to the US showroom in Chicago by 40-tonne (six-axle) truck (1270 km). Table B9 of Appendix B gives the energy/tonne·km for ocean shipping and truck transport. The car has a useful life of 10 years, and will be driven on average 20,000 km per year, consuming 2 MJ/km. Assume that recovery and shredding at end of life consumes 0.5 GJ but recovers materials with an energy credit of 25 GJ per vehicle.



Make an energy-audit bar chart for the car with bars for material, manufacture, distribution, use, and disposal. Which phase of life consumes most energy? The inherent uncertainty of current data for embodied and processing energies is considerable—if both of these were in error by up to 20% either way, could you still draw firm conclusions from the data? If so, what steps would do most to reduce life-energy requirements?

E8.6. Making an eco-audit (4): family car. The following table lists one European automaker's summary of the material content of a gasoline-powered midsize family car. Material proxies for the vague material descriptions are given in parentheses and italicized. The vehicle is gasoline powered and weighs 1800 kg. Retrieve data for the embodied energy of the materials from Appendix B, Table B2, and use them to calculate the total embodied energy of the vehicle. Retrieve the energy/tonne·km consumed by a family car from Table B9 and use it to calculate the use energy, assuming the car is driven 25,000 km for 10 years. Hence, make a comparison of the embodied and the use energy, highlighting ways in which the total could be reduced.

Material content of a family car, total weight 1800 kg

Material	Mass (kg)
Steel (<i>low-alloy steel</i>)	950
Aluminum (<i>cast aluminum alloy</i>)	438
Thermoplastic polymers (<i>PU</i>)	148
Thermosetting polymers (<i>polyester</i>)	93
Elastomers (<i>butyl rubber</i>)	40
Glass (<i>borosilicate glass</i>)	40
Other metals (<i>copper</i>)	61
Textiles (<i>polyester</i>)	47
Total mass	1800

PU, polyurethane.

E8.7. Making an eco-audit (5): patio heaters. The patio heater shown here is manufactured in Southeast Asia and shipped by bulk carrier 10,570 km to the United States, where it is sold and used. It weighs 24 kg, of which 17 kg is rolled stainless steel, 6 kg is rolled carbon steel, 0.6 kg is cast brass, and 0.4 kg is unidentified injection-molded plastic, so we will use polypropylene as a proxy to deal with this. The masses, materials, and processes are listed in the table.



In use, the heater delivers 14 kW of heat (“enough to keep eight people warm”), consuming 0.9 kg of LPG per hour, releasing 3.03 kg of CO₂/kg of gas. The heater is used for 3 hours per day for 30 days per year, over 5 years, at which time the owner tires of it and dumps it. We will ignore end of life. Use these data plus carbon footprints for materials and processes from Appendix B, Tables B2 and B6, to construct a bar chart for the CO₂ emission of one heater over its life.

Bill of materials and processes, patio heater

Material	Mass (kg)
Stainless steel, rolled	17
Carbon steel, rolled	6
Brass, cast	0.6
Polymer molded (<i>polypropylene</i>)	0.4
Total	24

E8.8. Making an eco-audit (6): ceramic pottery kilns. Kilns for firing pottery are simple structures, but they are large and heavy, and that means a lot of material goes into making them. Is this a case in which the embodied energy of the materials dominates the life energy? An energy audit will tell.



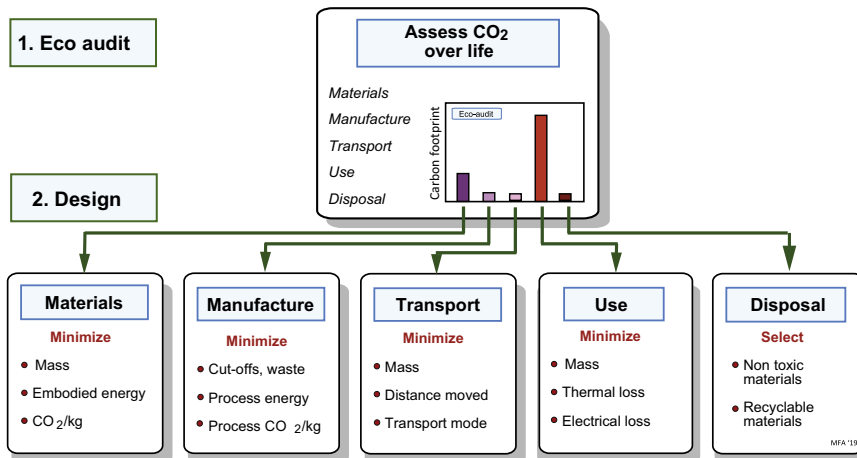
At basis a kiln is a steel frame lined with refractory brick enclosing the chamber in which the ceramics are fired. Nichrome heating elements are embedded in the inner face of the brick and connected to a power source with insulated copper cable. The chamber is closed during firing by a brick-lined door. The table lists the principal materials of a small pottery kiln capable of firing a chamber of 0.28 m^3 (10.5 ft^3) at up to 1200°C . It is rated at 12 kW. In a typical firing cycle the kiln operates at full power (12 kW) for 4.5 hours to get the interior up to 1200°C and then reduces to 4.9 kW to maintain this temperature for a further 3.5 hours, after which power is cut, using a total of 71 kWh per firing.

We will suppose that the kiln is installed in an art school, and used once per week for 40 weeks per year. The kiln life is 10 years.

Bill of materials		
Component	Recycle content (%)	Part mass (kg)
Mild steel frame and casing	40%	65
Refractory brick	0%	350
Nichrome furnace windings	0%	5
Copper connectors	40%	2
Alumina high-temperature insulation	0%	1
	Total	423

E8.9. Making an eco-audit (7). Carry out an eco-audit for a product of your choosing. Either pick something simple with little or no use energy (a plastic bowl, for example) or, more ambitiously, something more complex and be prepared to dismember it, weigh the parts, and use your judgment to decide what they are made of and how they were shaped and their energy requirement for use.

Material selection strategies



CONTENTS

- 9.1 Introduction and synopsis
- 9.2 Function, constraints, objectives, and free variables
- 9.3 Material property charts
- 9.4 Selection criteria and property charts
- 9.5 Resolving conflicting objectives: trade-off methods
- 9.6 Computer-aided selection
- 9.7 Summary and conclusions
- 9.8 Further reading
- 9.9 Appendix: Deriving material indices
- 9.10 Exercises

9.1 Introduction and synopsis

Life is full of decisions. Which shoes to buy? Which restaurant to eat at? Which camera? Which university? Most of us evolve strategies for reaching decisions, some involving an emotional response ("It's cool—Joe/Joanna has one"), others based on cold logic.

It's cold logic that we want here. The strategy then takes the following form:

- Identify the function of the object you aim to choose—what is it for? What should it do?
- List the constraints: the characteristics that the object must have to satisfy your requirements.
- Formulate the objective: the criterion you will use to rank the candidates that meet the constraints.
- Research documentation for the top-ranked candidates to satisfy yourself that nothing has been overlooked.

This chapter is about using this function—constraints—objectives—documentation strategy. It follows naturally from the eco-audits of the previous chapters in the way illustrated by the cover picture, itself an expansion of the two-part strategy of Fig. 7.2. The first part, the eco-audit, identifies the phase of

life that has the greatest eco-impact. The second is a response to the eco-audit. If material production is the dominant phase, then the logical way forward is to choose materials with low embodied energy and carbon footprint and to use less of them. If manufacture is an important energy-using phase of life, more efficient processing becomes the prime target. If transport makes a large contribution, then seeking a more efficient transport mode or reducing transport distance becomes the first priority. When the use phase dominates, the strategy is that of

- minimizing mass and rolling resistance if the product is part of a system that moves,
- increasing thermal efficiency if the product is a thermal or thermomechanical system, or
- reducing electrical losses if the product is an electromechanical system.

The best material choice to reduce one bar of the eco-audit will not be the one that minimizes the others, requiring trade-off methods to reach a compromise. And there is always cost: the most eco-benign choice of material is not always the cheapest. There the trade-offs can be more difficult.

9.2 Function, constraints, objectives, and free variables

Function. There is a story about a man—his name was Claude Shannon—who invented a product with only one function. It was a box with a switch on the front. When you pressed the switch, the box opened, a hand came out, switched off the switch, and went back inside. If you pressed the switch after that, nothing happened. Just one function. Once.

Some products are like that: air bags, for example, or disposable diapers, or, notoriously, single-use packaging. But most of the things engineers design function more than once, and many have more than one function. Typical functions are to support a load, to contain a pressure, to transmit heat, to provide electrical insulation, and so forth. This must be achieved subject to constraints: that certain dimensions are fixed; that the component must carry the design loads without failure, must insulate against or conduct heat or electricity, must work safely in a certain range of temperatures and in a given environment; and many more. In designing the component, the designer has one or more objectives: to make it as cheap as possible, perhaps, or as light, or as environmentally benign, or some combination of these. Certain parameters can be adjusted to optimally meet the objective; the designer is free to vary dimensions that are not constrained by design requirements and, most importantly, free to choose the material for the component. We call these free variables. Constraints, objectives, and free variables ([Table 9.1](#)) define the boundary conditions for selecting a material and—in the case of load-bearing components—the choice of shape for its cross section. We refer to this step of reexpressing design requirements in terms of function, constraints, objectives, and free variables as that of translation.

Table 9.1 Function, constraints, objectives, and free variables

Function	■ What does the component do?
Constraints	■ What nonnegotiable conditions must be met?
Objective	■ What is to be maximized or minimized?
Free variables	■ What parameters of the problem is the designer free to change?

It is important to be clear about the distinction between constraints and objectives. A constraint is an essential condition that must be met, usually expressed as an upper or lower limit on a material property. An objective is a quantity for which an extreme value (a maximum or minimum) is sought, frequently the minimization of cost, mass, volume, or—of particular relevance here—environmental impact (Table 9.2).

Table 9.2 Examples of common constraints and objectives

Common constraints		Common objectives
Must be ■ <i>Electrically conducting</i> ■ <i>Optically transparent</i> ■ <i>Corrosion resistant</i> ■ <i>Nontoxic</i> ■ <i>Nonrestricted substance</i> ■ <i>Able to be recycled</i> ■ <i>Biodegradable</i>	Binary (Yes/No) constraints	Minimize ■ Cost ■ Mass ■ Volume ■ Thermal losses ■ Electrical losses ■ Resource depletion ■ Energy consumption ■ Carbon emissions ■ Waste ■ Environmental impact ■ Water use
Must meet a target value of ■ <i>Stiffness</i> ■ <i>Strength</i> ■ <i>Fracture toughness</i> ■ <i>Thermal conductivity</i> ■ <i>Service temperature</i>		Quantitative constraints

Example: Translation of the design requirements for the wheeled bin of Fig. 8.1

A material is required to make large wheeled bins that are picked up and emptied by mechanisms attached to a garbage truck.

Function	■ Contain refuse hygienically until collected
Constraints	■ Withstand rough handling
	■ Chemically resistant to all household waste
	■ Able to be recycled
	■ Able to be molded in very large numbers
Objective	■ As cheap as possible
Free variables	■ Choice of material

Translation. Every household has at least one such bin provided by local authority, so low cost and long life are priorities. The bin must be robust enough to survive mechanical handling and must not corrode or degrade in contact with household waste, including food waste. The bin must be recyclable at end of life to avoid landfill problems and CO₂ release by combustion. Its curved shape requires that the material it is made from can be molded.

Function, constraints, objectives, and free variable for the bin.

Screening. Constraints are gates: meet the constraint and you pass through the gate, fail to meet it and you are shut out. Screening (Fig. 9.1) does just that: it eliminates candidates that cannot do the job at all because one or more of their attributes lies outside the limits set by the constraints. As examples, the requirements that the bin “withstand rough handling” and is “chemically resistant to household waste” impose lower limits on the attributes of toughness and corrosion resistance that successful candidates must meet. The left-hand column of Table 9.2 lists common constraints.

Ranking: material indices. To rank the materials that survive the screening step we need criteria of excellence—what we have called objectives. The right-hand column of Table 9.2 lists common objectives. Each is a measure of performance. Performance is sometimes limited by a single material property, sometimes by a combination of them. Thus the best materials to minimize thermal losses (an objective) are those with the smallest values of thermal conductivity, λ . The best materials to minimize DC electrical losses (another objective) are those with the lowest electrical resistivity, ρ_e —provided, of course, that they also meet all other constraints imposed by the design. Here the objective is met by selecting the material with an extreme (here, the lowest) value of a single property. Often, though, it is not one property but a group of properties that are relevant. Thus the best materials for a light, stiff tie-rod are those with the

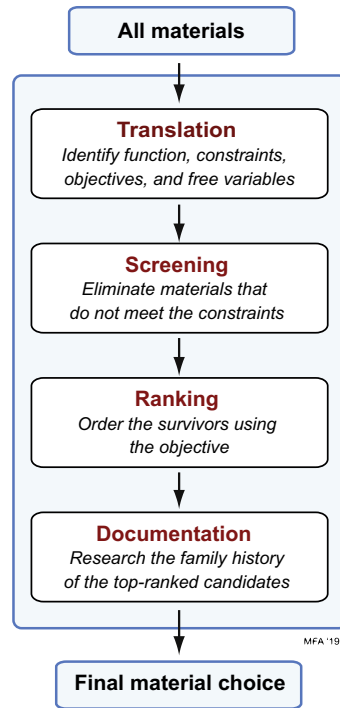
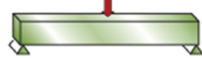
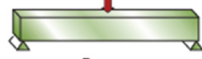
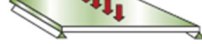


FIGURE 9.1 The strategy. There are four steps. All can be implemented in software, allowing large populations of materials to be investigated.

smallest value of the group, ρ/E , where ρ is the density and E is Young's modulus. Those for a strong beam of lowest embodied energy are those with the lowest value of $H_m \rho / \sigma_y^{2/3}$, where H_m is the embodied energy of the material and σ_y is its yield strength. The property or property group that maximizes performance for a given design is called its material index.

Table 9.3 lists indices for stiffness and strength-limited design for three generic components, a tie, a beam, and a panel, for each of five objectives. The first four relate to design for the environment. Selecting materials with the objective of minimizing volume uses as little material as possible, conserving resources. Selection with the objective of minimizing mass is central to the eco-design of transport systems (or indeed of anything that moves), because fuel consumption for transport scales with weight. Selection with the objective of minimizing embodied energy and carbon emission is important when large quantities of material are used, as they are in construction of buildings, bridges, roads, and other infrastructure. The fifth column, selection with the objective of minimizing cost, is always an additional objective.

Table 9.3 Indices for mechanical (stiffness and strength-limited) design

		Objective: To minimize				
	Mode of loading	Volume	Mass	Embodied energy	Carbon footprint	Material cost
Stiffness-limited design	Tie 	$1/E$	ρ/E	$H_m\rho/E$	$CO_2\rho/E$	$C_m\rho/E$
	Beam 	$1/E^{1/2}$	$\rho/E^{1/2}$	$H_m\rho/E^{1/2}$	$CO_2\rho/E^{1/2}$	$C_m\rho/E^{1/2}$
	Panel 	$1/E^{1/3}$	$\rho/E^{1/3}$	$H_m\rho/E^{1/3}$	$CO_2\rho/E^{1/3}$	$C_m\rho/E^{1/3}$
Strength-limited design	Tie 	$1/\sigma_y$	ρ/σ_y	$H_m\rho/\sigma_y$	$CO_2\rho/\sigma_y$	$C_m\rho/\sigma_y$
	Beam 	$1/\sigma_y^{2/3}$	$\rho/\sigma_y^{2/3}$	$H_m\rho/\sigma_y^{2/3}$	$CO_2\rho/\sigma_y^{2/3}$	$C_m\rho/\sigma_y^{2/3}$
	Panel 	$1/\sigma_y^{1/2}$	$\rho/\sigma_y^{1/2}$	$H_m\rho/\sigma_y^{1/2}$	$CO_2\rho/\sigma_y^{1/2}$	$C_m\rho/\sigma_y^{1/2}$

CO_2 (kg/kg), carbon footprint; ρ (kg/m³), density; E (GPa), elastic (Young's) modulus; H_m (MJ/kg), embodied energy/kg; C_m (\$/kg), material price; σ_y (MPa), yield strength.

Table 9.4 Indices for thermal design

Objective: To minimize			
Objective	Steady-state heat loss	Thermal inertia	Heat loss in a thermal cycle
Index	λ	$C_p \rho$	$(\lambda C_p \rho)^{1/2}$

λ (W/m·K), thermal conductivity; $a = \lambda/C_p \rho$ (m²/s), thermal diffusivity; C_p (J/kg·K), specific heat.

Table 9.4 lists indices for thermal design. The first is a single property, the thermal conductivity, λ ; materials with the lowest values of λ minimize heat loss at steady state, that is, when the temperature gradient is constant. The other two guide material choice when the temperature fluctuates.

There are many such indices, each associated with maximizing some aspect of performance. They provide criteria of excellence that allow ranking of materials by their ability to perform well in the given application. Their derivation is described in the appendix to this chapter, and their use is illustrated by case studies in Chapter 10. All can be plotted on material property charts to identify the best candidates. Charts for the indices of Tables 9.3 and 9.4 appear later in this chapter (Section 9.6).

To summarize, then: screening uses constraints to isolate candidates that are capable of doing the job; ranking uses an objective to identify the candidates that can do the job best.

Example: Screening and ranking for wheeled bin

A search for tough materials that can be molded and have excellent resistance to water, wine, dilute acids, and dilute alkali delivers the following list:

Material	Price (\$/kg)
Polypropylene	1.4
Polyethylene	1.6
Poly(vinyl chloride)	2.6
Acrylonitrile butadiene styrene	3
Polychloroprene (Neoprene)	4.7
Polytetrafluoroethylene (Teflon)	13
Polyether ether ketone	92

The constraints have reduced the number of viable materials to seven candidates. When ranked by price, as in this table, the top-ranked candidates are polypropylene, polyethylene, and poly(vinyl chloride).

Documentation. The outcome of the steps so far is a short-list of candidates that meet the constraints and are ranked most highly by the objective. You could just choose the top-ranked candidate, but what hidden weaknesses might it have? What is its reputation? Does it have a good track record? To get further, we seek a detailed profile of each: its documentation (Fig. 9.1, bottom).

What form does documentation take? Typically it is descriptive, graphical, or pictorial: case studies of previous uses of the material, failure analyses, details of its corrosion behavior in particular environments, details of its availability and pricing, warnings of its environmental impact or toxicity, or descriptions of how it is recycled. Such information is found in handbooks, suppliers' data sheets, websites of environmental agencies, and other high-quality websites. Documentation helps narrow the short-list to a final choice, allowing a definitive match to be made between design requirements and material choice.

Why are all these steps necessary? Without screening and ranking, the candidate pool is enormous and the volume of documentation is overwhelming. Dipping into it, hoping to stumble on a good material, gets nowhere. But once a small number of potential candidates have been identified by the screening—ranking steps, detailed documentation can be sought for these few alone, and the task becomes viable.

Example: Documentation for materials for the wheeled bin

At this point it helps to know how the three top-ranked candidates listed in the last Example box are used. A quick Web search reveals the following.

Polypropylene: garden furniture, washing machine tanks, wet-cell battery cases, pipes and pipe fittings, car bumpers.

Polyethylene: oil containers, street bollards, beer crates.

Poly(vinyl chloride): pipes, canoes, vinyl flooring, windows and cladding.

This is encouraging: the first two materials, particularly, have a history of use in applications requiring toughness and durability. We select these two, confident that they best meet the constraints and minimize the objective that we set out in the Translation step.

Using indices for scaling. Most of the products we use today were designed when the dominant objectives were those of minimizing cost and maximizing performance and safety. It is only now that the objective of minimizing environmental impact has been added to the list. An eco-audit or full life-cycle assessment of these products identifies the phase of life that is causing most damage, and often suggests that replacing the materials of which the product is made with a set that is lighter or has a lower carbon footprint would reduce the eco-burden.

But substitution is not that simple. The density of aluminum is one-third that of steel, so you might think that the weight of a car body made of aluminum would

be one-third of one made of steel. But aluminum is less than half as stiff and (depending on the alloy and heat treatment) about half as strong as steel. If the car body is to function as well after the substitution as it did before, the section thickness of the aluminum components must be increased to compensate for the poorer properties. Thick sections are heavier than thin ones, so the reduction in weight is not nearly as large as it at first appeared. And there is something else to remember: aluminum costs, per kilogram, three times more than steel. Substitution is seldom cost neutral. What, then, are the scaling laws when one material is replaced by another? And what is the gain in eco-performance when property compensation is properly included? Indices can tell us.

The factor by which the mass of a tie, beam, or panel is changed by substitution is given by the ratio of the index for the new material to that for the old one. The factors by which embodied energy, carbon footprint, or material cost are changed by substitution are similarly given by the ratios of the relevant indices. Here are two examples.

Example: Weight savings by material substitution

A steel beam, loaded in bending, is to be replaced by an aluminum one to save weight. The beam stiffness must remain unchanged. What is the maximum potential weight savings that this substitution allows? Here are the material properties.

Material	Density ρ (kg/m ³)	Modulus E (GPa)
Steel	7850	210
Aluminum	2710	70

Answer. From Table 9.3, the ratio of the mass after substitution to that before is:

$$\frac{m_1}{m_o} = \frac{\rho_1}{\rho_o} \left(\frac{E_o}{E_1} \right)^{1/2} = 0.6$$

Here the subscript “o” refers to steel, the subscript “1” to aluminum. Inserting the data gives the ratio 0.6, meaning that the maximum possible weight savings is 40%, rather than the factor of 3 that the ratio of the densities suggests.

Example: Volume savings by material substitution

Standard polystyrene foam is used as thermal insulation for a small refrigerator. The foam has a thermal conductivity $\lambda_o = 0.035$ W/m·°C. It is suggested that the same thermal performance with thinner walls (increasing the useful volume) could be obtained by using instead a polymethacrylimide foam, which has a thermal

conductivity $\lambda_1 = 0.028 \text{ W/m} \cdot ^\circ\text{C}$. By what factor can the wall thickness be reduced by this substitution while maintaining the same thermal performance as before?

Answer. From Table 9.4, the ratio of wall thicknesses that will give the same heat loss per unit area is:

$$\frac{t_1}{t_o} = \frac{\lambda_1}{\lambda_o} = 0.8$$

The substitution allows the walls to be made 20% thinner than before.

9.3 Material property charts

Material property charts were introduced in Chapter 6. They are of two types: bar charts and bubble charts. A bar chart is simply a plot of one or a group of properties—Chapter 6 has several of them. Bubble charts plot two properties or groups of properties. Constraints and objectives can be plotted on them.

Five material property charts guide materials selection to minimize mass, material carbon footprint, and thermal losses using the indices of Tables 9.3 and 9.4. They are a subset of a much larger collection that can be found in the texts listed under Further reading at the end of this chapter.¹

The modulus–density chart (Fig. 9.2). The modulus E of engineering materials spans seven decades,² from 0.0001 GPa to nearly 1000 GPa; the density ρ spans a factor of 2000, from less than 10 to 20,000 kg/m³. The chart shows how members of each family cluster together, each occupying a characteristic part of the chart. The members of the ceramics and metals families have high moduli and densities; none have a modulus less than 10 GPa or a density less than 1700 kg/m³. Polymers, by contrast, all have moduli below 10 GPa and densities that are lower than those of any metal or ceramic; most are close to 1000 kg/m³. Elastomers have roughly the same density as other polymers but their moduli are lower by a further factor of 100 or more. Materials with a lower density than polymers are porous: human-made foams and natural cellular structures like wood and cork.

This chart lets you select materials to minimize the mass of stiffness-limited structures. To do that you need the three indices for lightweight, stiffness-limited design in Table 9.3. Guidelines showing the slope of each of these are

¹Some of charts can be downloaded, free, from grantadesign.com/education.

²Very-low-density foams and gels (which can be thought of as molecular-scale, fluid-filled, foams) can have lower moduli than this. As an example, gelatin (as in Jell-O) has a modulus of about 10^{-5} GPa.

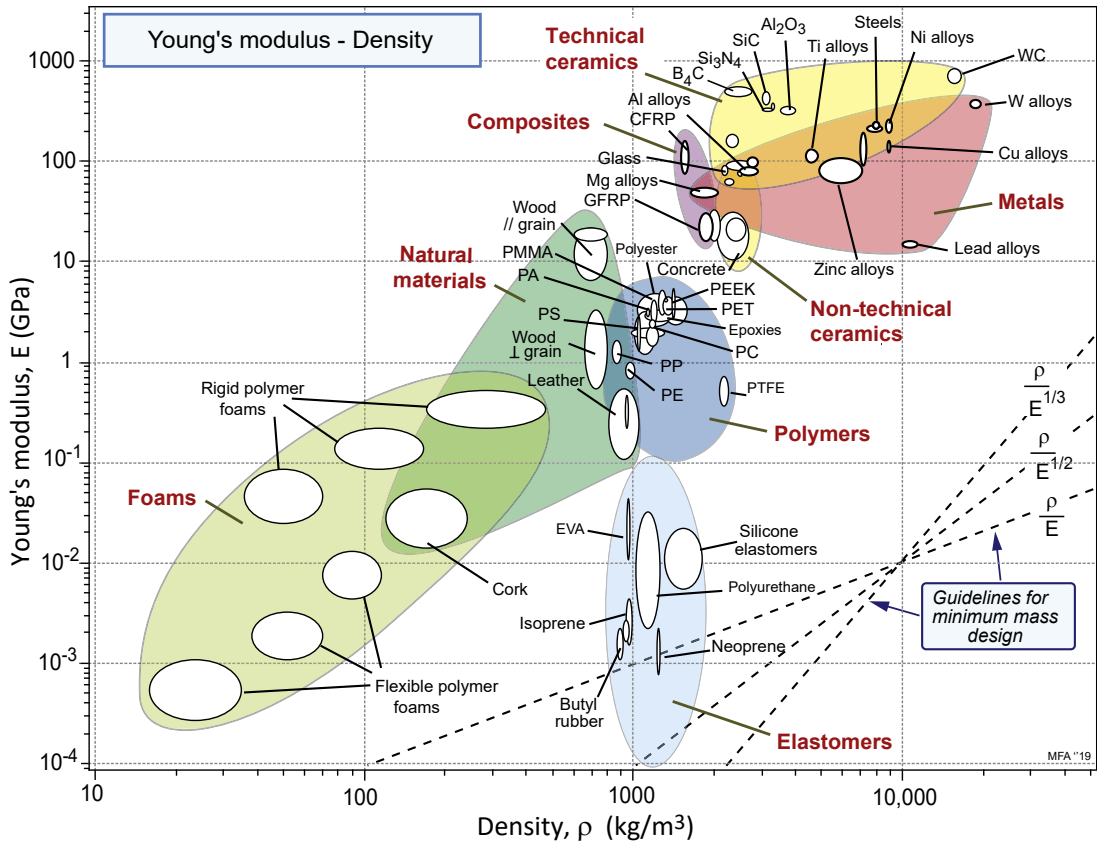


FIGURE 9.2 *The modulus—density chart. It allows selection for stiffness at minimum weight.*

plotted on the chart. You might think that most structures are strength, not stiffness, limited, but that is wrong. Stiffness determines not only elastic deflection under load but also vibration frequencies and resistance to buckling.

The strength–density chart (Fig. 9.3). The range of the yield strength σ_y or elastic limit σ_{el} of engineering materials, like that of the modulus, spans about six decades: from less than 0.01 MPa for foams, used in packaging and energy-absorbing systems, to 10^4 MPa for diamond, exploited in diamond tooling for machining and polishing. Members of each family again cluster together in characteristic areas of the chart.

Comparison with the modulus–density chart (Fig. 9.2) reveals some marked differences. The modulus of a solid is a well-defined quantity with a narrow range of values. The yield strength has a wider spread. The strength range for a given class of metals, such as stainless steels, can span a factor of 10 or more, depending on its state of work hardening and heat treatment; it is this that leads to the elongated strength bubbles for metals. Polymers cluster together with strengths between

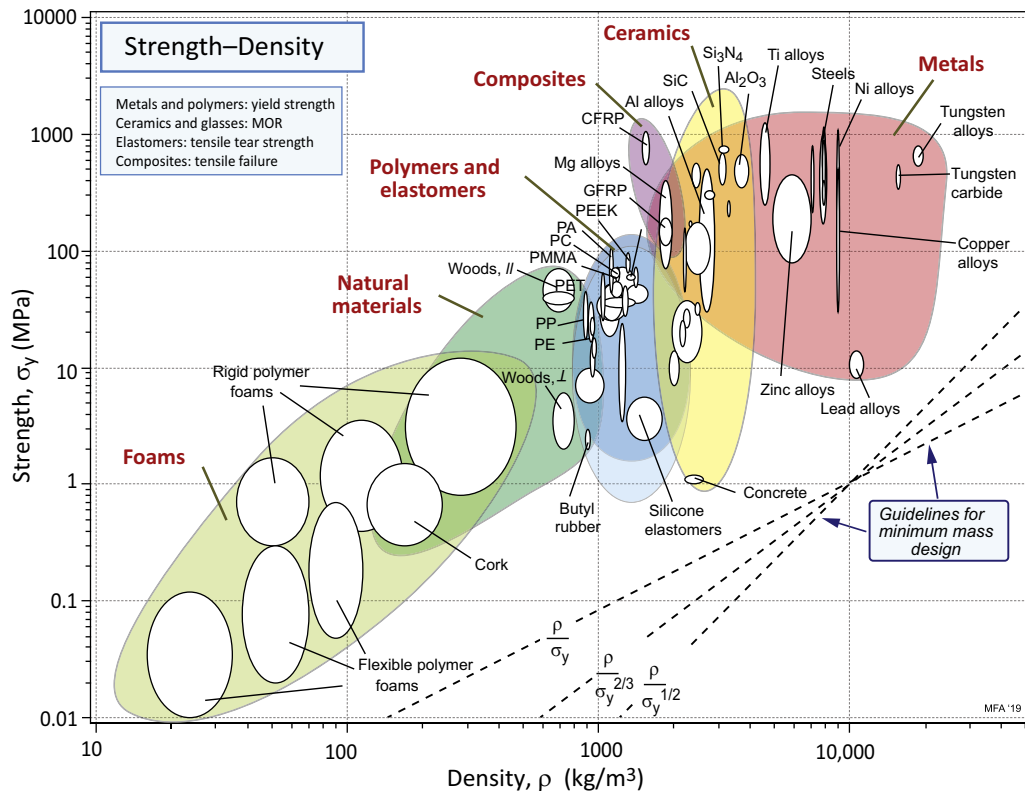


FIGURE 9.3 The strength–density chart. It allows selection for strength at minimum weight (MOR, Modulus of Rupture).

10 and 100 MPa. The composites carbon fiber–reinforced plastic and glass fiber–reinforced polymer have strengths that lie between those of polymers and ceramics, as one might expect, since they are mixtures of the two.

This chart is the one for selecting materials to minimize the mass of strength-limited structures. To do that you need the three indices for lightweight, strength-limited design in Table 9.3. Guidelines showing the slope of each of these are plotted on the chart.

The modulus–carbon footprint and strength–carbon footprint charts (Figs. 9.4 and 9.5). The two charts just described guide design to minimize mass. If the objective becomes minimizing the carbon footprint of the material of the product, we need equivalent charts for these. The first, Fig. 9.4, shows modulus plotted against carbon footprint per unit volume, $CO_2 \cdot \rho$, where CO_2 is the carbon footprint per kilogram of the material. The second, Fig. 9.5, does the same for strength. Guidelines show the slopes associated with the indices of Table 9.3.

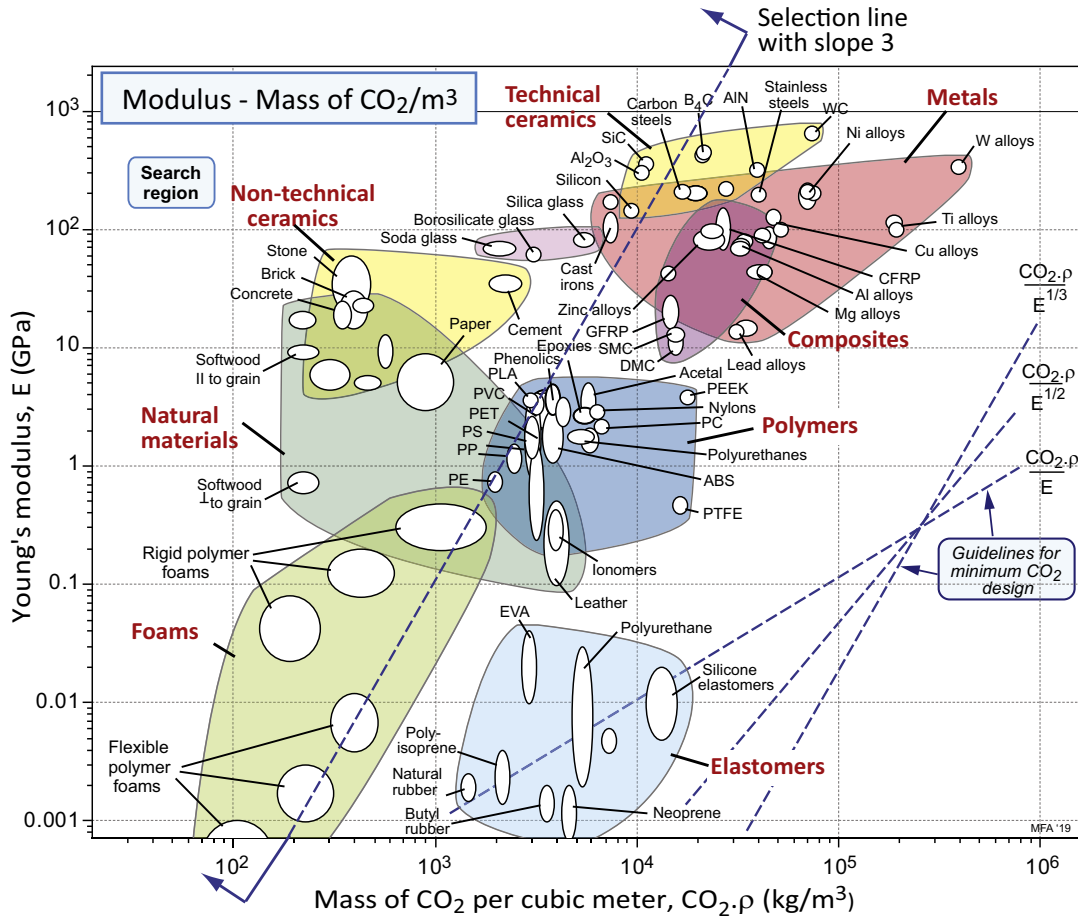


FIGURE 9.4 The modulus–carbon footprint chart. It allows selection for stiffness with minimum carbon emission.

The thermal conductivity–thermal diffusivity chart (Fig. 9.6). The thermal conductivity, λ , is the material property that governs the flow of heat, q (W/m^2), in a steady temperature gradient, dT/dx :

$$q = -\lambda \frac{dT}{dx} \quad (9.1)$$

The thermal diffusivity, a (m^2/s), is the property that determines how quickly a thermal front diffuses into a material. It is related to the conductivity:

$$a = \frac{\lambda}{C_p \rho} \quad (9.2)$$

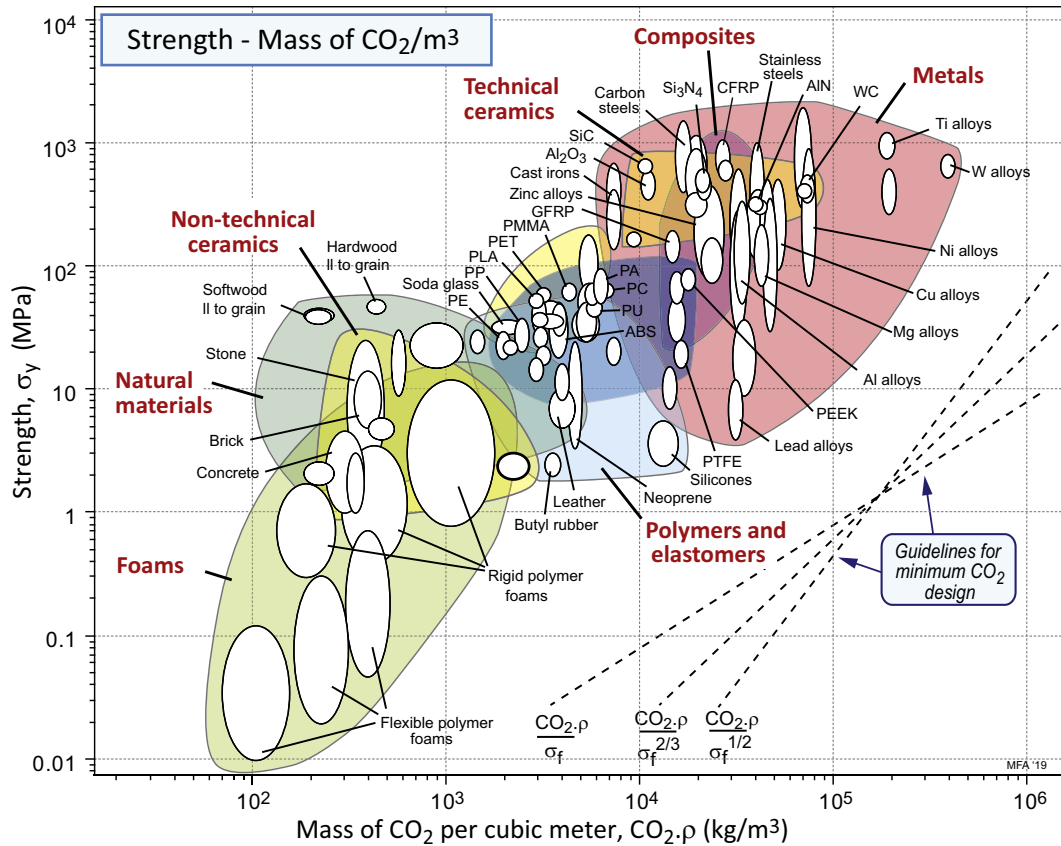


FIGURE 9.5 The Strength–Carbon footprint chart. It allows selection for strength with minimum carbon emission.

where C_p is the specific heat per unit mass ($\text{J/kg} \cdot \text{K}$). The contours show the volumetric specific heat, ρC_p , equal to the ratio of the two, λ/α . The data span almost five decades in λ and α . Solid materials are strung out along the line:

$$\rho C_p \approx 3 \times 10^6 \text{ J/m}^3 \text{ K} \quad (9.3)$$

meaning that the heat capacity per unit volume, ρC_p , is almost constant for all solids, something to remember for later. As a general rule, then,

$$\lambda = 3 \times 10^6 a$$

(λ in $\text{W/m} \cdot \text{K}$ and a in m^2/s). Some materials deviate from this rule: they have lower-than-average volumetric heat capacity.

The largest deviations are shown by porous solids: foams, low-density firebrick, woods, and the like. Because of their low density, they contain fewer atoms per

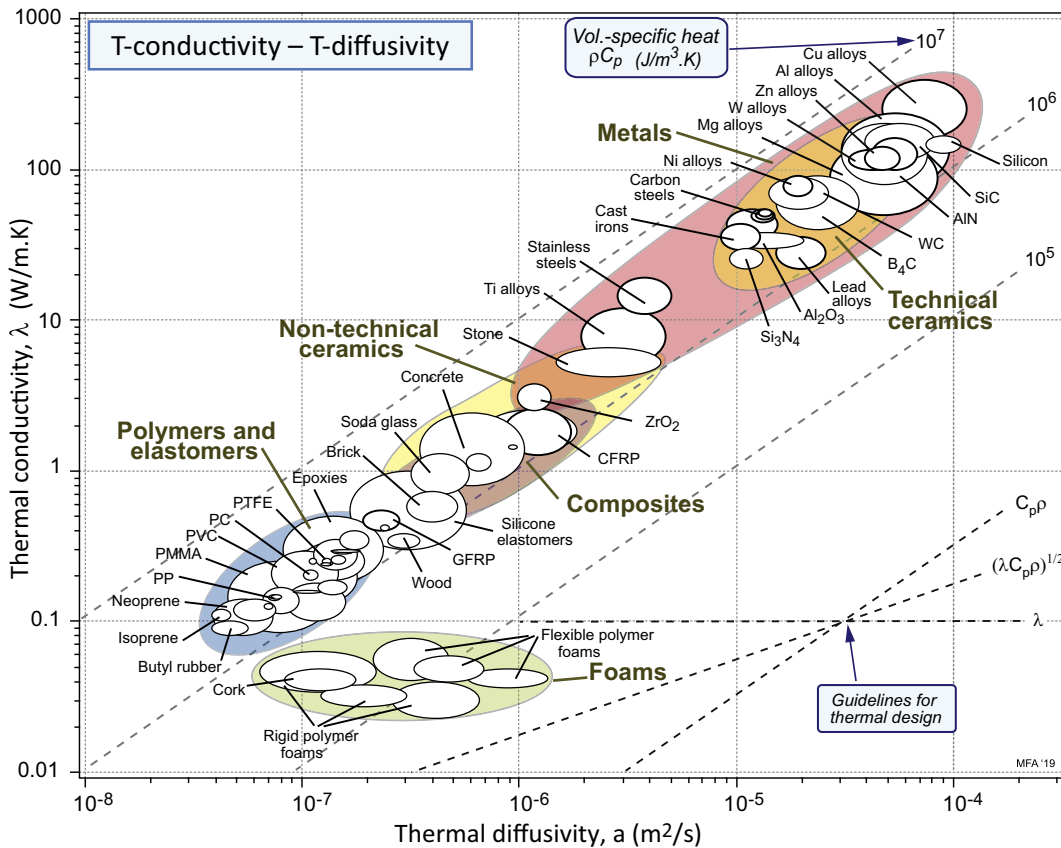


FIGURE 9.6 The thermal conductivity–thermal diffusivity chart with contours of volumetric specific heat. It allows selection for minimum thermal loss.

unit volume and, averaged over the volume of the structure, ρC_p is low. The result is that although foams have low conductivities (and are widely used for insulation because of this), their thermal diffusivities are not necessarily low. This means that they do not transmit much heat, but they heat up or cool down quickly.

9.4 Selection criteria and property charts

Screening: constraints on charts. Design requirements impose nonnegotiable demands (“constraints”) on the material of which the product is made. These limits can be plotted as horizontal or vertical lines on material property charts. Fig. 9.7 is a schematic of the modulus–density chart shown earlier. We suppose

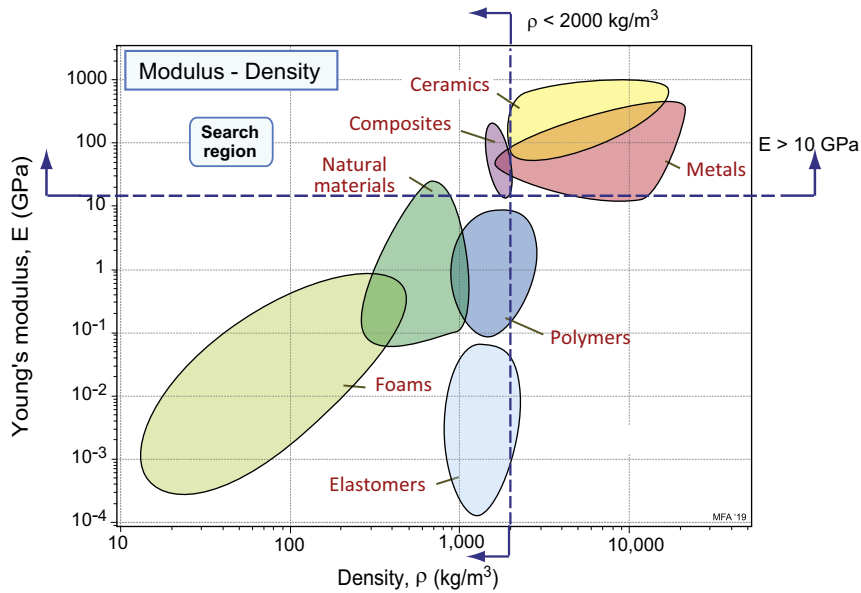


FIGURE 9.7 Screening using a bubble chart. The materials in the “search region” at the upper left meet the constraints modulus >10 GPa and density <2000 kg/m³.

that the design imposes limits on these of modulus >10 GPa and density <2000 kg/m³, shown on the figure. The materials in the “search region” at the upper left meet these constraints.

Ranking: indices on charts. Material indices measure performance. They allow ranking of the materials that meet the constraints of the design. We use the design of light, stiff components as examples; the other material indices are used in a similar way.

The logarithmic scales of the modulus–density chart allow the three indices $M = \rho/E$, $\rho/E^{1/3}$, and $\rho/E^{1/2}$, listed in Table 9.3, to be plotted onto it. Consider the first of these:

$$M = \rho/E \quad (9.4)$$

Taking logs:

$$\log(E) = \log(\rho) - \log(M) \quad (9.5)$$

For a given value of M , this is the equation of a straight line of slope 1 on a plot of $\log(E)$ against $\log(\rho)$, as shown in Fig. 9.8. Similarly, the condition:

$$M = \frac{\rho}{E^{1/3}} = \text{constant}, C \quad (9.6)$$

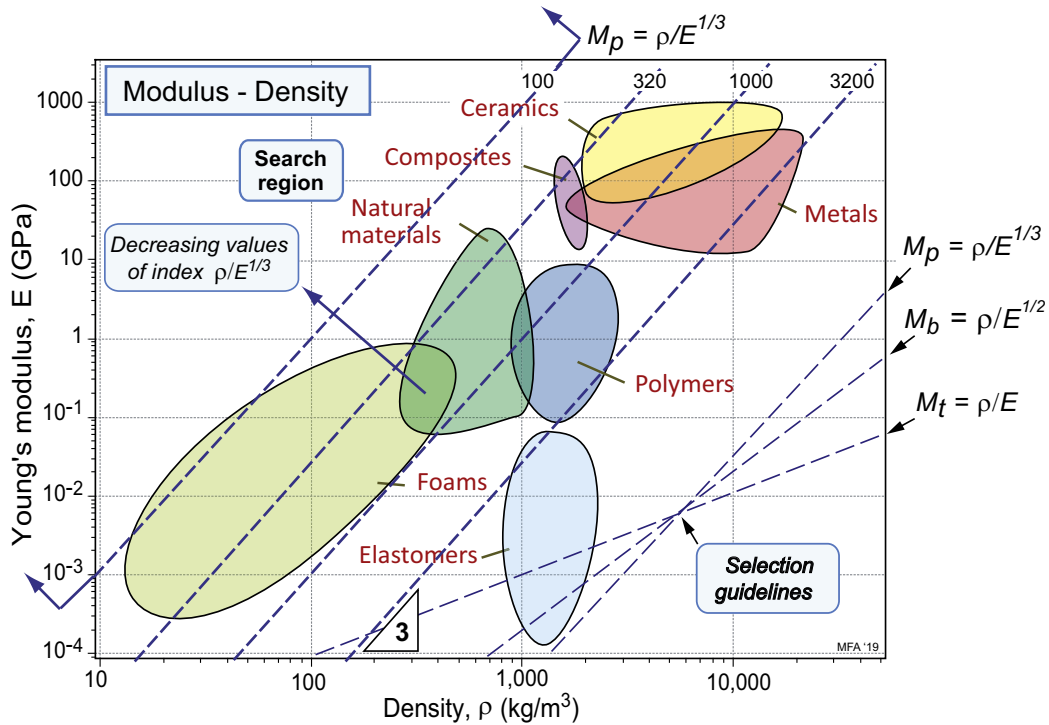


FIGURE 9.8 A schematic $E - \rho$ chart showing selection guidelines for the three material indices for stiff, lightweight structures on a grid of lines for the index $\rho/E^{1/3}$.

becomes, on taking logs,

$$\log(E) = 3 \log(\rho) - 3 \log(C) \quad (9.7)$$

This is another straight line, this time with a slope of 3, also shown. By inspection, the third index $\rho/E^{1/2}$ will plot as a line of slope 2. We refer to these lines as selection guidelines. They give the slope of the family of parallel lines belonging to that index, each line corresponding to a different value of the index M . Selection guidelines are marked on the charts shown earlier in this chapter.

It is now easy to read off the subset of materials that maximize performance for each loading geometry. For example, all the materials that lie on a line of constant $M = \rho/E^{1/3}$ perform equally well as a light, stiff panel; those above the line perform better; those below, less well. The upper part of Fig. 9.8 shows a grid of lines corresponding to values of $M = \rho/E^{1/3}$.

Example: use of the eco-charts

Which polymer, in sheet form, offers the lowest carbon footprint per unit of bending stiffness?

Answer. Table 9.3 gives the index for stiffness at minimum carbon footprint for a panel in bending:

$$M = \frac{CO_2 \cdot \rho}{E^{1/3}}$$

Selecting the corresponding guideline and displacing it to the left until only one polymer remains above it identifies PLA (polylactide—a biopolymer) as the best choice (Fig. 9.9)

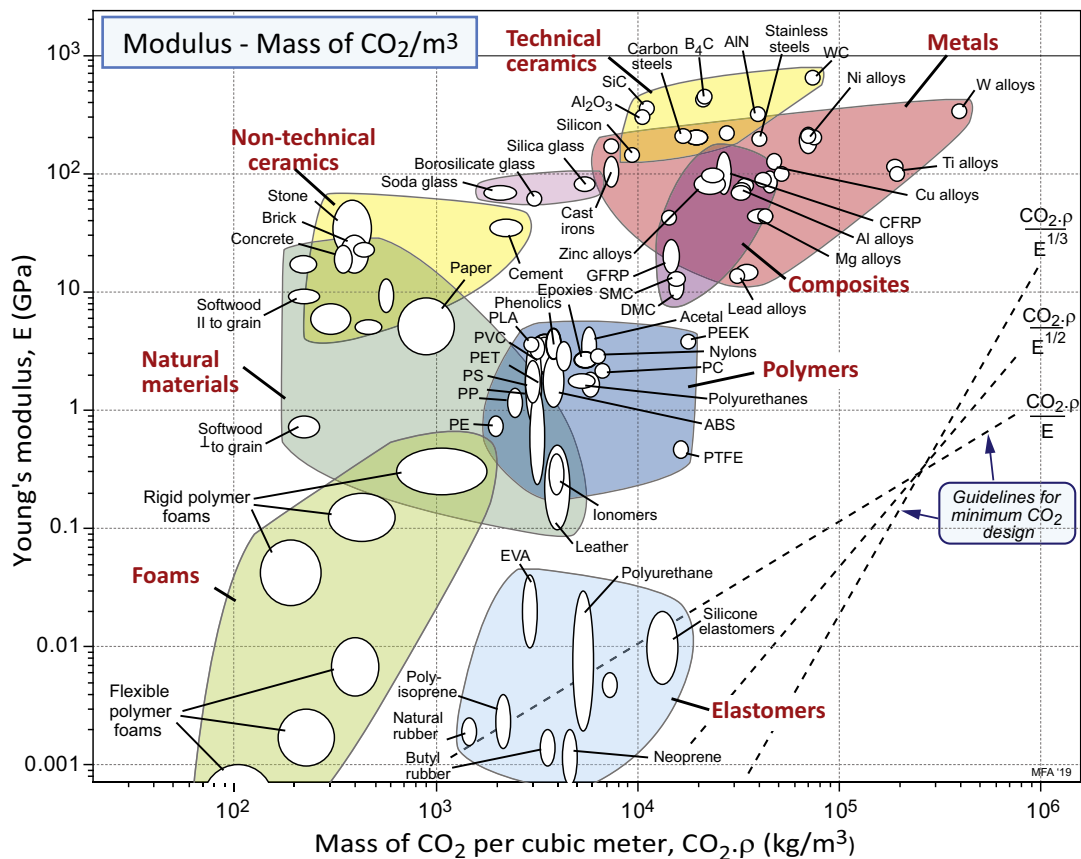


FIGURE 9.9 Selection of materials that minimize carbon emission for a given stiffness.

9.5 Resolving conflicting objectives: trade-off methods

Real-life materials selection almost always requires that a compromise be reached between conflicting objectives: Table 9.2 listed 11 of them. The choice of materials that best meets one objective will not usually be that which best meets the others; the lightest material, for instance, will generally not be the cheapest or the one with the lowest carbon footprint. To make any progress, the designer needs a way of trading mass against cost and both against carbon footprint. This section describes ways of resolving this and other conflicts that arise when objectives compete.

Systematic trade-off strategies. Consider the choice of material to minimize both mass (performance metric P_1) and cost (performance metric P_2) while also meeting a set of constraints such as a required strength or durability in a certain environment. Following the standard terminology of optimizations theory, we define a solution as a viable choice of material meeting all the constraints but not necessarily optimal by either of the objectives. Fig. 9.10, left, is a plot of P_1 against P_2 for alternative solutions, each bubble describing a solution. The solutions that minimize P_1 do not minimize P_2 , and vice versa. Some solutions, such as that at region A, are far from optimal—all the solutions in the box attached to it have lower values of both P_1 and P_2 . Solutions like A are said to be dominated by others. Solutions like those at region B have the characteristic that no other solutions exist with lower values of both P_1 and P_2 . These are said to be nondominated solutions. The line or surface on which they lie is called the nondominated or optimal trade-off line. The values of P_1 and P_2 corresponding to the nondominated set of solutions are called the Pareto set.

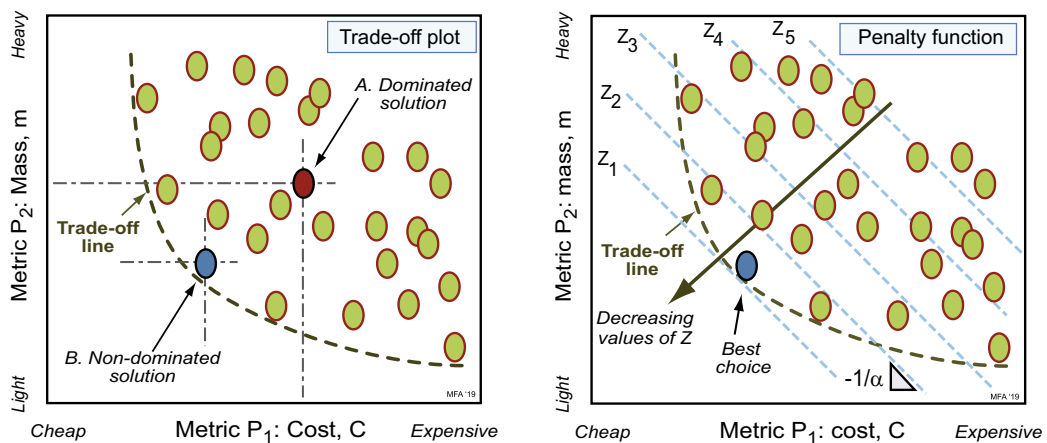


FIGURE 9.10 (Left) Multiple objectives. Mass and cost for a component made from alternative material choices. The trade-off surface links nondominated solutions. (Right) The penalty function identifies the optimal choice.

The solutions on or near the trade-off line offer the best compromise; the rest can be rejected. Often this is enough to identify a short-list, using intuition to rank them. When it is not, the strategy is to define a penalty function.

Penalty functions. Consider first the case in which one of the objectives to be minimized is cost, C (unit: \$), and the other is mass, m (unit: kg). We define a locally linear penalty function³ Z :

$$Z = C + \alpha_m m \quad (9.8)$$

Here α_m is the change in Z (\$) associated with unit increase in m (kg) and has the unit of \$/kg. It is called an “exchange constant.” Rearranging gives:

$$m = -\frac{1}{\alpha_m} C + \frac{1}{\alpha_m} Z. \quad (9.9)$$

This defines a linear relationship between m and C that plots as a family of parallel penalty lines each for a given value of Z , as shown on the right of Fig. 9.10. The slope of the lines is the negative reciprocal of the exchange constant, $-1/\alpha_m$. The value of Z decreases toward the bottom left: the best choices lie there. The optimum solution is the one nearest the point at which a penalty line is tangential to the trade-off line, since it is the one with the smallest value of Z .

If instead the two objectives were cost C (\$) and carbon footprint CO_2 (kg), the penalty function becomes:

$$Z = C + \alpha_c CO_2 \quad (9.10)$$

Here the exchange constant, α_c , is the change in Z for unit increase in CO_2 , and thus again has the unit of \$/kg. Contours of Z can be plotted on a chart of mass versus carbon footprint, just as in the previous example.

When all three objectives are active the penalty function becomes:

$$Z = C + \alpha_m m + \alpha_c CO_2 \quad (9.11)$$

It can no longer be plotted as contours on a two-dimensional chart, but it can be evaluated for candidate materials, choosing the one that minimizes Z . To do this we need values for α_m and α_c .

Values for the exchange constants α_m and α_c . An exchange constant is the value or “utility” of a unit change in a performance metric. In the example we have just seen, α_m is the utility (\$) of saving 1 kg of weight. Its magnitude depends on the application. Thus, the utility of weight savings in a family car is small, though significant; in aerospace it is much larger. The utility of heat transfer in house insulation is directly related to the cost of the energy used to heat the house; that in a heat exchanger for electronics can be much higher because high heat

³Also called a *value function* or *utility function*. The method allows a local minimum to be found. When the search space is large, it is necessary to recognize that the values of the exchange constants α_i may themselves depend on the values of the performance metrics P_i .

transfer allows faster data processing, something worth far more. The utility can be real, meaning that it measures a true savings of cost. But it can also, sometimes, be perceived, meaning that the consumer, influenced by scarcity, advertising, or fashion, will pay more than the true value of the performance metric.

In many engineering applications, the exchange constants can be derived approximately from technical models for the life cost of a system. The utility of weight savings in transport systems is derived from the value of the fuel saved or that of the increased payload, evaluated over the life of the system. Table 9.5 gives approximate values for α for various modes of transport. The most striking thing about them is the enormous range: the exchange constant depends in a dramatic way on the application in which the material will be used. It is this that lies behind the difficulty in adopting aluminum alloys for cars despite their universal use in aircraft, it explains the much greater use of titanium alloys in military than in civil aircraft, and it underlies the restriction of beryllium (a very expensive metal) to use in space vehicles.

Exchange constants can be estimated approximately in various ways. The cost of launching a payload into space lies in the range \$3000 to \$10,000/kg; a reduction of 1 kg in the weight of the launch structure would allow a corresponding increase in payload, giving the ranges of α_m shown in the table. Similar arguments based on increased payload or decreased fuel consumption give the values shown for civil aircraft, commercial trucks, and automobiles. The values change with time, reflecting changes in fuel costs, legislation to increase fuel economy, and the like.

There are other circumstances in which establishing the exchange constant can be more difficult. An example is that of environmental impact—the damage to the environment caused by manufacture, or use, or disposal of a given product. Minimizing carbon emission has now become an important objective, almost as important as minimizing cost. Ingenious design can reduce the first without driving the second up too much. But how much is unit decrease in carbon emission worth?

Table 9.5 Exchange constants α_m for the mass–cost trade-off for transport systems

Sector: Transport system	Basis of estimate	Exchange constant, α_m (US\$/kg)
Family car	Fuel savings	1–2
Truck	Payload	5–20
Civil aircraft	Payload	100–500
Military aircraft	Payload, performance	500–1000
Space vehicle	Payload	3000–10,000

Exchange constants for eco-design. One outcome of the Kyoto Protocol (see Chapter 5) was the creation of a market in carbon permits. A carbon permit to emit 1 tonne of CO₂ per year sells today (June 2019) for €20 (\$24, or £18). Not all emitters of carbon have to hold carbon permits—ordinary households, for example, are exempt—but those that do not are now threatened with a carbon tax (at this writing aiming for €20 per tonne). The permit price or tax sets a value for the carbon-to-currency exchange constant, α_c , important because the penalty function can now be evaluated, allowing a properly balanced trade-off.

Using penalty functions (1)

The exchange constant for weight savings in a light truck is $\alpha_m = \$12/\text{kg}$, meaning that the value of weight reduction over the life of the vehicle is \$12 for each kilogram saved. A maker of such vehicles offers three models. The first uses steel panels for the body work. The second uses aluminum, costs \$2500 more, but weighs 300 kg less. The third offers carbon-fiber paneling, costs \$8000 more and weighs 500 kg less. Which is the best buy?

Answer. The penalty functions for the steel (1) and aluminum (2) vehicles are

$$Z_1 = C_1 + \alpha_m m_1$$

and

$$Z_2 = C_2 + \alpha_m m_2$$

The aluminum vehicle is attractive only if its value of Z is lower than that of the steel one. In writing:

$$\begin{aligned}\Delta Z &= Z_2 - Z_1 = C_2 - C_1 + \alpha_m(m_2 - m_1) \\ &= 2500 - 12 \times 300 = -\$1100\end{aligned}$$

The aluminum-paneled vehicle offers a life savings of \$1100—it is a good buy. Repeating the comparison for the composite-paneled vehicle gives a value of $\Delta Z = +\$2500$. It is not a good buy.

Using penalty functions (2)

If a European-wide carbon tax of €20/tonne is applied to material production, will it result in a significant rise in material prices? Express the result as a percentage increase above the current untaxed price.

Answer. Form a penalty function using $\alpha_c = \$0.02/\text{kg}$ as the carbon-to-price exchange constant:

$$Z = C_m + 0.02 \times CO_2,$$

where C_m is the material price in \$/kg and CO_2 is its carbon footprint in kg/kg. Rearranging to express Z as a percentage increase in C_m gives:

$$\left(\frac{Z - C_m}{C_m} \right) \times 100 = \frac{2 \times CO_2}{C_m}.$$

This quantity is plotted in Fig. 9.11. The tax results in a 20% increase in the price of cement, a 10% increase in the price of aluminum and magnesium, and lesser, but still significant, increases in the price of the other materials.

9.6 Computer-aided selection

The charts in Section 9.3 give an overview of materials and their properties, but the number of materials that can be shown on any one of them is obviously limited.

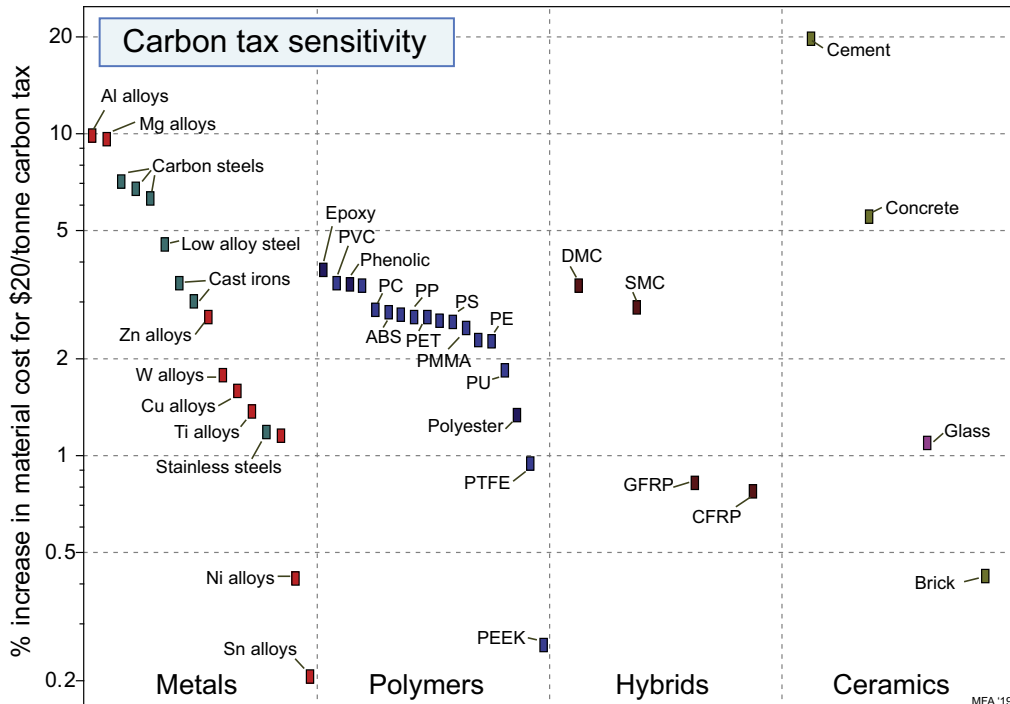


FIGURE 9.11 The percentage increase in material cost for a \$20/tonne carbon tax.

Selection using them is practical when there are very few constraints, but when there are many—as there usually are—checking that a given material meets them all is cumbersome. Both problems are overcome by a computer implementation of the method.

The CES material selection software is one such implementation (Fig. 9.12). Its databases contain records for materials. It has a search and selection engine. It has plotting facilities to make material property charts and the ability to plot material indices on the charts and use them to optimize material selection, implementing the strategy of this chapter. More information can be found at grantadesign.com/education.

9.7 Summary and conclusions

This chapter describes a broad strategy for selecting materials.

- Decide on the attributes the material must (or must not) have, defining a set of constraints.
- Apply the constraints, leaving a list of candidate materials that meet them.

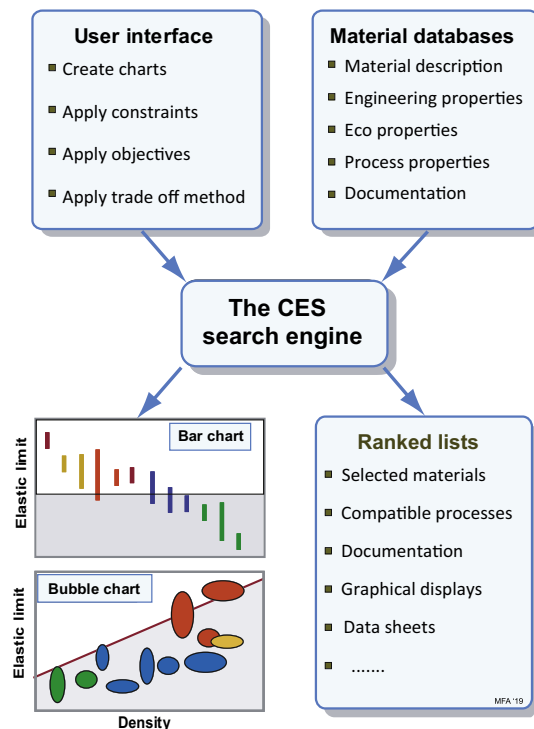


FIGURE 9.12 The operation and outputs of a typical selector software.

- Decide on an objective—a measure of excellence. It could be price (the cheaper the better), or weight (the lighter the better), or eco-impact (the lower the carbon footprint the better), or some other measure of performance. Use this to rank the list of surviving candidates.
- Research the top three or four on the list, gathering as much information as possible, to make a well-informed final choice.

There are, usually, many constraints, but this does not create a difficulty: simply apply them sequentially, retaining only the materials that meet them all. Often, too, there are two or more objectives, and that does create a problem: the choice that best satisfies one is rarely the best choice for the other. Then trade-off methods become useful. They can be graphical, by plotting the alternatives, identifying the trade-off line, and then using judgment to select candidates on or near the line. Or they can be analytical, by formulating a penalty function and seeking the candidates that carry the lowest penalty.

Now we have a set of tools. In Chapter 10 they are used to analyze and select materials for design for the environment.

9.8 Further reading

- Ashby, M.F. (2017), "Materials selection in mechanical design", 5th edition, Butterworth Heinemann, Oxford, UK. (*A text that develops the ideas presented here in more depth, including the derivation of material indices, a discussion of shape factors, and a catalog of simple solutions to standard problems.*)
- Ashby, M.F., Shercliff, H.R., and Cebon, D. (2019) "Materials: engineering, science, processing and design", 4th edition, Butterworth Heinemann, Oxford, UK. (*An elementary text introducing materials through material property charts, and developing the selection methods through case studies.*)
- Dieter, G.E. (2000) "Engineering design, a materials and processing approach", 3rd edition, McGraw-Hill, New York, pp. 150–153 and 255–257. (*A well-balanced and respected text, now in its 3rd edition, focusing on the role of materials and processing in technical design.*)
- Goicoechea, A., Hansen, D.R., and Druckstein, L. (1982) "Multi-objective decision analysis with engineering and business applications", Wiley, New York. (*A good starting point for the theory of multi-objective decision-making.*)
- Keeney, R.L. and Raiffa, H. (1993) "Decisions with multiple objectives: preferences and value tradeoffs", 2nd edition, Cambridge University Press, Cambridge, UK. (*A notably readable introduction to methods of decision-making with multiple, competing objectives.*)

9.9 Appendix: Deriving material indices

This appendix describes how material indices are derived. You can find out more about them and their use in the first two texts listed under "Further reading". Here we give three examples.

The performance of a component is characterized by a performance equation called the objective function. The performance equation contains a group of material properties. This group is the material indices of the problem. Sometimes the "group" is a single property. If the performance of a uniform beam is measured by its stiffness, the performance equation contains only one property, the elastic modulus E . More commonly the performance equation contains a group of two or more properties. Familiar examples are the specific stiffness, E/ρ (where ρ is the density) and the specific strength, σ_y/ρ (where σ_y is the yield strength or elastic limit), but there are many others. For reasons that will become apparent, we express the indices in a form for which a minimum, not a maximum, is sought.

Recall that the life energy and emissions for transport systems are dominated by the fuel consumed during use. The lighter the system is made, the less fuel it consumes and the less carbon it emits. So a good starting point is minimum weight design, subject, of course, to the other necessary constraints, of which the most important, here, have to do with stiffness and strength. We consider the generic components shown in Fig. 9.13: a tie, a panel, and a beam, loaded as shown. The derivation, when the objective is that of minimizing embodied energy, carbon footprint, or material cost, follows in a similar way.

- (a) Material indices for stiffness and strength at minimum mass: simple section shapes

A light, stiff tie-rod. A material is sought for a cylindrical tie-rod that must be as light as possible (Fig. 9.13A). Its length L_o is specified and it must carry a tensile

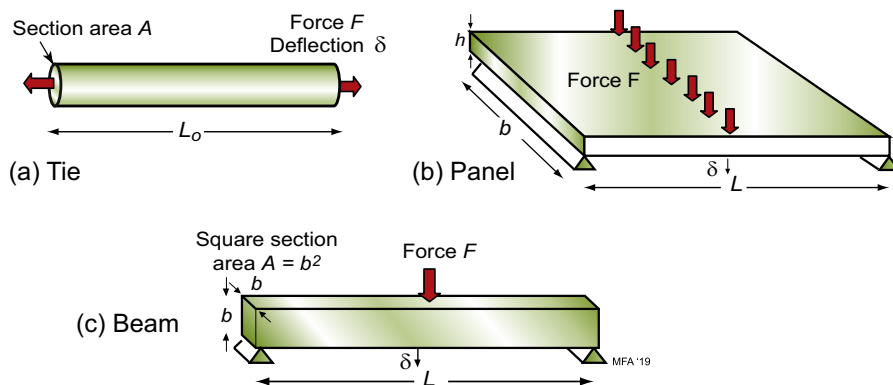


FIGURE 9.13 Generic components with simple section shapes. (A) A tie, a tensile component. (B) A panel, loaded in bending. (C) A beam, loaded in bending.

Table 9.6 Design requirements for the light, stiff tie

Function	Tie-rod
Constraints	Stiffness S^* specified (a functional constraint) Length L_o specified (a geometric constraint)
Objective	Minimize mass
Free variables	Choice of material Choice of cross-section area A

force F without extending elastically by more than δ . Its stiffness must be at least $S^* = F/\delta$. We are free to choose the cross-section area A and, of course, the material of which it is made. The design requirements, translated, are listed in Table 9.6.

The objective function describes the quantity to be minimized, here the mass m of the tie:

$$m = AL_o\rho, \quad (9.12)$$

where ρ is the density of the material of which the tie is made. We can reduce the mass by reducing the cross-section, but there is a constraint: the section area A must be sufficient provide a stiffness $S^* = F/\delta$. The stiffness of a tie is:

$$S = \frac{AE}{L_o}, \quad (9.13)$$

where E is Young's modulus. If the material has a low modulus E , a large cross-section A is needed to give the necessary stiffness; if E is high, A can be smaller. The area required to provide at least the stiffness S^* is:

$$A \geq \frac{L_o S^*}{E}.$$

Inserting this into Eq. (9.12) gives:

$$m \geq S^* L_o^2 \left(\frac{\rho}{E} \right). \quad (9.14)$$

Both S^* and L_o are specified. The lightest tie that meets the design requirements is that made of the material with the smallest value of the index:

$$M_{t_1} = \frac{\rho}{E}, \quad (9.15a)$$

provided that they also meet all other constraints of the design. If the constraint is not stiffness but strength, the index becomes:

$$M_{t_2} = \frac{\rho}{\sigma_y}, \quad (9.15b)$$

where σ_y is the yield strength. The best choice of material for the lightest tie that can support a load F without yielding is that with the smallest value of this index.

The mode of loading that most commonly dominates in engineering is not tension, but bending—think of floor joists of buildings, of wing spars of aircraft, of shafts of golf clubs and racquets, of door panels for cars. The index for bending differs from that for tension, and this changes the optimal choice of material.

A light, stiff panel. A panel is a flat slab, like a table top. Its length L and width b are specified, but its thickness h is free. It is loaded in bending by a distributed load F per unit width (Fig. 9.13B). The stiffness constraint requires that it must not deflect more than δ . The objective is to achieve this with minimum mass, m . Table 9.7 summarizes the design requirements.

The objective function for the mass of the panel is the same as that for the tie:

$$m = AL\rho = bhL\rho.$$

Its bending stiffness S must be at least S^* :

$$S = \frac{C_1 EI}{L^3} \geq S^*. \tag{9.16}$$

Here C_1 is a constant that depends only on the distribution of the loads and I is the second moment of area, which, for a rectangular section $b h$, is:

$$I = \frac{bh^3}{12}. \tag{9.17}$$

We can reduce the mass by reducing h , but only so far that the stiffness constraint is still met. Using the last two equations to eliminate h in the objective function gives:

$$m \geq \left(\frac{12 S^*}{C_1 b} \right)^{1/3} (bL^2) \left(\frac{\rho}{E^{1/3}} \right). \tag{9.18}$$

Table 9.7 Design requirements for the light, stiff panel	
Function	Panel
Constraints	Stiffness S^* specified (a functional constraint) Length L and width b specified (a geometric constraint)
Objective	Minimize mass
Free variables	Choice of material Choice of panel thickness h

The quantities S^* , L , b , and C_1 are all specified; the only freedom of choice left is that of the material. The best materials for a light, stiff panel are those with the smallest values of:

$$M_{p1} = \frac{\rho}{E^{1/3}}. \quad (9.19a)$$

Repeating the calculation with a constraint of strength rather than stiffness leads to the index:

$$M_{p2} = \frac{\rho}{\sigma_y^{1/2}}. \quad (9.19b)$$

These don't look much different from the previous indices, ρ/E and ρ/σ_y , but they are: they lead to different choices of material. For now, note the procedure. The in-plane dimensions of the panel were specified, but we were free to vary the thickness h . The objective is to minimize its mass, m . Use the stiffness constraint to eliminate the free variable, here h . Then read off the combination of material properties that appears in the objective function—the equation for the mass. It sounds easy, and it is, so long as you are clear from the start what the constraints are, what you are trying to maximize or minimize, and which parameters are specified and which are free. The beam (Fig. 9.13C) is analyzed in a similar way, given the indices listed in Table 9.3.

(b) Indices for stiffness and strength at minimum material embodied energy, carbon footprint, or cost

We've done all the hard work. Extending the ideas to minimizing the material embodied energy H_m or carbon footprint CO_2 or price C_m to product life is just a case of replacing density ρ in the indices derived so far with $H_m\rho$ or $CO_2\rho$ or $C_m\rho$. Here is the argument. When the objective is to minimize embodied energy rather than mass, the indices change. If the embodied energy of the material is H_m MJ/kg, the energy embodied in a component of mass m is just mH_m . The objective function for the energy H embodied in the tie, panel, or beam then becomes:

$$H = mH_m = ALH_m\rho. \quad (9.20)$$

Proceeding along the same steps as for minimum mass then leads to indices that have the form of Eqs. (9.15) and (9.19) with ρ replaced by $H_m\rho$, as in Table 9.3. Minimizing carbon footprint or cost follows the same procedure, replacing H_m MJ/kg with the material footprint CO_2 kg/kg or the material cost C_m in the indices. It must be remembered that the material cost is only part of the cost of a shaped component; there is also the manufacturing cost—the cost to shape, join, and finish it.

9.10 Exercises

E9.1. Objectives and constraints: What is meant by an objective and what by a constraint in the requirements for a design? How do they differ? How are they used?

E9.2. Free variables: What is meant by a free variable? Give examples of free variables.

E9.3. Objectives: Bikes come in many forms, each aimed at a particular sector of the market:

- sprint bikes
- touring bikes
- mountain bikes
- shopping bikes
- children's bikes
- folding bikes

Use your judgment to identify the primary constraints and objective that you would apply in selecting a material for the frame for the differing bike types.

E9.4. Translation (1). Describe and illustrate the Translation step of the material selection strategy. Materials are required to make safe, eco-friendly swings and climbing frames for a children's playground. How would you translate these design requirements into a specification for selecting materials?

E9.5. Translation (2). You are asked to design a cooking pan for camping. What constraints would you apply in selecting a material for the pan? What objectives would you use to rank the materials that meet the constraints?



E9.6. Translation (3). A material is required for a disposable fork for a fast-food chain that is conscious of its environmental image. List the objective and the constraints that you would see as important in this application.

E9.7. Translation (4). Storage heaters capture heat in a core and then release it, usually to an airstream, when required. A design for a sustainable storage heater, heated electrically with power from solar panels during the day, specifies low carbon footprint and low cost as requirements. The heating

element reaches a maximum temperature of 200°C. Translate this description into a function, constraints, objectives, and free variable for selecting a material for the core.

E9.8. Material indices. What is meant by a material index?

E9.9. Selecting an index. The function of the outer screen casing of an ultrathin portable computer is to protect the screen from external loads. If it deflects too much when loaded in bending, the screen will suffer. The casing is a panel with prescribed in-plane dimensions. The objective is that of minimizing the panel thickness h while meeting a constraint on elastic bending stiffness, S^* . What is the appropriate material index?

E9.10. Using indices (1). Use the E - CO_2 ρ chart of Fig. 9.4 to find the metals with a modulus E greater than 100 GPa and the lowest carbon footprint per unit volume.

E9.11. Using indices (2). Use the σ_y - CO_2 ρ chart of Fig. 9.5 to find polymers with a low value of the material index for low-carbon-footprint beams, $(CO_2\rho)/(\sigma_y)^{2/3}$, where CO_2 is the carbon footprint of the material, ρ is its density, and σ_y is its yield strength.

E9.12. Using indices (3). Plot the index for a light, stiff panel on a copy of the modulus–density chart of Fig. 9.2, positioning the line such that only a few materials are left above it. Exclude ceramics and glass because of their brittleness. Which six do you find? What material classes do they belong to?



E9.13. Using indices (4). Panels are needed to board up the windows of an unused building. The panels should have the lowest possible carbon footprint but be strong enough to deter an intruder who, in attempting to break in, will load the panels in bending. Which index would you choose to guide choice?

Plot the index on the strength–carbon footprint chart of Fig. 9.5, positioning the line to find the best choice, excluding ceramics because of their brittleness. Which six do you find? What material classes do they belong to?

E9.14. Materials substitution (1). A steel beam, loaded in bending, is to be replaced by an aluminum one to save weight. The bending strength of the beam must remain unchanged. What is the maximum potential weight savings that this substitution allows? Here are the material properties.

Material	Density ρ (kg/m ³)	Strength σ_y (MPa)
Steel YS260	7850	288
Aluminum 6061-T4	2710	113

E9.15. Material substitution (2). The Guggenheim Museum in Bilbao, Spain, is clad with titanium sheet. It is suggested that stainless steel sheet of the same thickness would be mechanically just as good and have a much lower carbon footprint. Is this statement accurate? Data for the two materials, taken from Appendix A, Table A2 and Appendix B, Table B2, are assembled in the table.

Material	Density ρ (kg/m ³)	Carbon footprint CO_2 (kg/kg)
Stainless steel	7700	5.4
Titanium	4600	36.0

E9.16. Material substitution (3). The person who suggested that stainless steel might be a more environmentally thoughtful choice now points out further that stainless steel has a higher modulus than titanium, so its substitution by stainless steel sheet of the same bending stiffness, rather than the same thickness, would make more sense. What is the ratio of carbon footprints per unit area when this comparison is made? The necessary data from Appendices A and B are assembled in the table.

Material	Density ρ (kg/m ³)	Carbon footprint CO_2 (kg/kg)	Young's modulus E (GPa)
Stainless steel	7700	5.4	200
Titanium	4600	36.0	110

E9.17. Eco-comparisons. A maker of polypropylene (PP) garden furniture is concerned that the competition is stealing part of his market by claiming that the “traditional” material for garden furniture, cast iron, is much less energy and CO₂ intensive than PP. A typical PP chair weighs 2 kg; one made of cast iron weighs 11 kg. Retrieve data for the two materials from Appendix B, Table B2, to find out who is right. Are the differences significant? (Remember the warning about precision at the start of Chapter 6.)

If the PP chair lasts 5 years and the cast iron chair lasts 25 years, does the conclusion change?

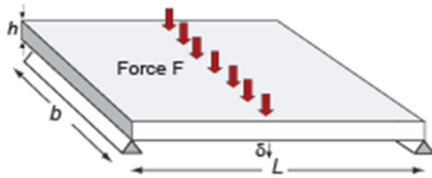
E9.18. Deriving indices. Show that the index for selecting materials for a strong panel with the dimensions shown here, loaded in bending, with minimum embodied energy content is:

$$M = \frac{\rho H_M}{\sigma_y^{1/2}},$$

where H_M is the embodied energy of the material, ρ its density, and σ_y its yield strength. To do so, rework the panel derivation in [Section 9.9](#), replacing the stiffness constraint with a constraint on failure load F , requiring that it exceed a chosen value F^* :

$$F = C_2 \frac{I \sigma_y}{hL} > F^*$$

Here C_2 is a constant and I is the second moment of area of the panel: $I = \frac{bh^3}{12}$.



Eco-informed material selection



CONTENTS

- 10.1 Introduction and synopsis
- 10.2 Which bottle is best? Selection per unit of function
- 10.3 Systematic eco-selection: carbonated-water bottles
- 10.4 Structural materials for buildings
- 10.5 Initial and recurring embodied energy of buildings
- 10.6 Heating and cooling (1): refrigeration
- 10.7 Heating and cooling (2): materials for passive solar heating
- 10.8 Heating and cooling (3): kilns and cyclic heating
- 10.9 Transport (1): introduction
- 10.10 Transport crash barriers—matching material to purpose
- 10.11 Transport (3): materials for lightweight structures

10.1 Introduction and synopsis

Eco-audits like those of Chapters 7 and 8 point the finger, directing attention to the life phase that is of most eco-concern. If you point fingers, you invite the response: What do you propose to do about it? Chapter 9 introduced the methods. Here we illustrate their use with case studies.

Remember, in reading them, that there is always more than one answer to environmental challenges. Cars can be made less polluting by making them out of lightweight materials. But they can also be made less polluting by replacing one way of powering them (the internal combustion engine, for example) with another (fuel cell/electric power, perhaps), even if this makes them heavier. And, of course, there is a third: change of lifestyle (no car at all). So while change of material is one option, change of concept is another.

Eco-friendly water bottles, pottery kiln, zero-carbon house (BBC News, July 2015), lightweight car.

10.12 Transport (4):
material substitution for
eco-efficient design

10.13 Summary and
conclusions

10.14 Further reading

10.15 Exercises

The case studies are in four groups:

- materials for drink containers (10.2, 10.3)
- materials for buildings (10.4, 10.5)
- heating and cooling (10.6–10.8)
- materials for transport (10.9–10.12)

The groups are self-contained. You can jump to the group that interests you without needing to read those that come before it. They are, however, arranged so that the simplest are at the beginning and the more complicated at the end.

10.2 Which bottle is best? Selection per unit of function

Newsclip: Small objects, big numbers. “A million bottles a minute: world’s plastic binge.”

More than 480bn plastic drinking bottles were sold in 2016 across the world. By 2021 this will increase to 580bn, according to Euromonitor International’s global packaging trends report.

The Guardian, June 28, 2017

The audit of the polyethylene terephthalate (PET) water bottle described in Chapter 7 delivered a clear message: the phase of life that dominates its energy consumption and CO₂ emission (Fig. 10.1) is that of producing the material of which the bottle is made. Drink containers are made from many different materials: glass, polyethylene, PET, aluminum, steel, laminated cardboard—Fig. 10.2 shows examples. Surely one material must be a better environmental choice than the others? Carbon footprints in kg/kg for the first five materials are listed in Table 10.1; they are taken from Appendix B, Table B2. The last, a Tetra Pak, is more difficult. Its “material” is a laminate of cardboard and aluminum-coated polyethylene. The Tetra Pak website¹ provides the value shown as the bottom line in Table 10.1.

Glass has the lowest carbon footprint, aluminum the highest. The material of the Tetra Pak is the second highest. But hold on. These are carbon per kilogram of material. The containers differ in weight and volume. What we need is the carbon per unit of function. The function of a bottle is to contain a fluid, so the proper metric for comparison is the carbon emission per unit volume of fluid contained.

The volumes, masses, and materials of the six competing container types are listed Table 10.1. For all six, cost-effective processes exist to make them. All but one—steel—resist corrosion in the mildly acidic or alkaline conditions

¹<https://www.tetrapak.com/sustainability/environmental-impact/a-value-chain-approach/carton-co2e-footprint>.

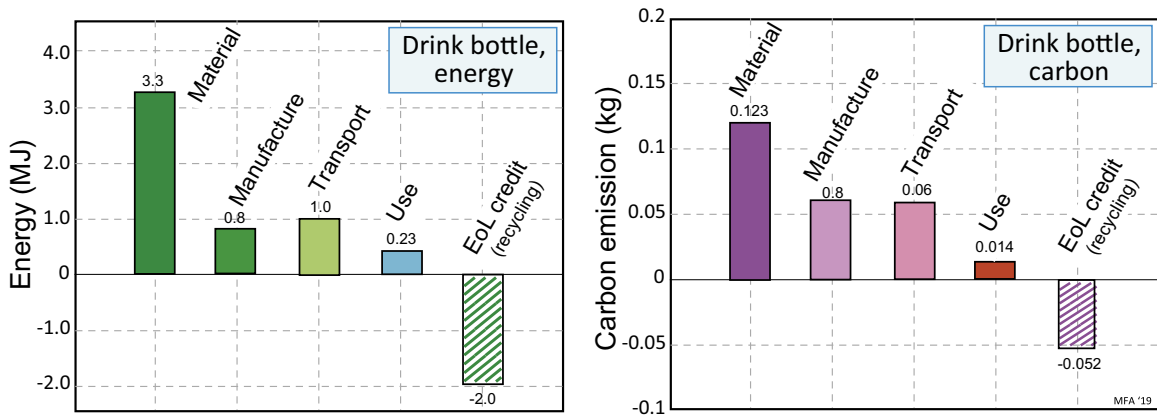


FIGURE 10.1 Energy and carbon audit of a drink bottle, recycled at end of life. EoL, end of life.



FIGURE 10.2 Containers for liquids: glass, polyethylene (PE), polyethylene terephthalate (PET), aluminum, steel, and cardboard. Which carries the lowest penalty of carbon emissions per unit volume of liquid?

characteristic of bottled drinks, but it is easily protected with lacquers. All claim that they can be recycled.

That leaves us with the objective. The last column of Table 10.1 lists the carbon emission per liter of fluid contained, calculated from the numbers in the other columns. The ranking is now very different: the laminated cardboard emerges as the best choice, polyethylene the next best. Glass (because so much is used to make one bottle) and aluminum (because of its high embodied energy) are the least good.

Postscript: In all discussion of this sort there are issues of primary and of secondary importance. There is cost: we have ignored this because eco-design was the prime objective. There is the economics of recycling: the value of recycled materials depends to differing degrees on impurity pickup. There is the fact that real cans and bottles are made with some recycled content, reducing the embodied

Table 10.1		Data for the containers with carbon footprints for virgin material		
Container type	Material	Mass (g)	Carbon footprint (kg/kg)	Carbon footprint (g/L)
PET 500-mL bottle	PET	25	2.7	135
PE 1-L milk bottle	High-density PE	30	2.8	84
Glass 750-mL bottle	Soda glass	325	0.76	247
Al 440-mL can	5000 series Al alloy	20	12	545
Steel 440-mL can	Plain carbon steel	45	2.3	235
Laminate 500-mL container ²	Cardboard/PE/Alu/PP	22	3.55	78

PE, *polyethylene*; PET, *polyethylene terephthalate*; PP, *polypropylene*.

energies of all six to varying degrees, but not enough to change the ranking. There is the extent to which current legislation subsidizes or penalizes one material or another (some nations tax plastic, others tax landfill). And there is appearance: transparency is attractive for some containers but irrelevant for others. But we should not let these cloud the primary findings: the lifetime carbon emission of a container is dominated by the material of which it is made, and that of the most eco-friendly containers can be less, by up to a factor of 5, than that of the least.

Newsclip: Small savings. Lighter bottle tops.

“It’s all change at the top for ASB Miller, brewer of Grolsch and Peroni. The company has developed a bottle cap that uses less steel, reducing its raw material costs and cutting carbon dioxide emissions, thanks to the lighter loads on delivery trucks. ... The group uses 42 billion tops a year.”

How impressed should we be by this headline? The crown caps referred to in the article weigh 2.5 g. Let us suppose a 20% weight savings: 0.5 g per cap. Multiplied by 42 billion, this gives 21,000 tonnes of steel. The first claim—that of reducing raw material costs for the cap makers—appears justified. What about the transport? A 500-mL (half-liter) bottle of beer weighs 310 g when empty and 810 g when full.

²<https://www.tetrapak.com/sustainability/environmental-impact/a-value-chain-approach/carton-co2e-footprint>.

Saving 0.5 g of steel per unit reduces its mass, and thus the transport energy and CO₂, by 0.06%. Much greater savings are possible by asking the driver of the delivery truck to drive slightly more slowly.

The Sunday Times, July 3, 2011

10.3 Systematic eco-selection: carbonated-water bottles

Carbonated drink bottles carry an internal pressure; they are pressure vessels. The ability to carry this pressure without bursting is an additional constraint—one not required of the six materials of the previous case study (Fig. 10.3). What's the best material for a bottle for carbonated water that will safely contain the pressure and is transparent, can be molded, and is recyclable (Table 10.2)?

The wall of a cylindrical bottle with an internal pressure p carries a circumferential stress $\sigma_c = pr/t$ and an axial stress $\sigma_a = pr/2t$, where r is the radius of the bottle and t its wall thickness. The wall must be thick enough to support the larger of these stresses without failing, requiring:

$$t = S \frac{pr}{\sigma_y}, \quad (10.1)$$

where σ_y is the yield strength of the wall material and S is a safety factor. The carbon associated with the material of the wall per unit area, $(CO_2)_{wall}$ (the quantity we want to minimize), is:

$$(CO_2)_{wall} = t(CO_2)\rho = S \frac{pr(CO_2)\rho}{\sigma_y}, \quad (10.2)$$

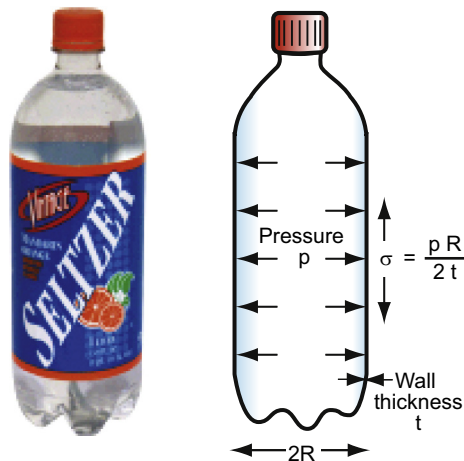


FIGURE 10.3 The walls of a pressurized bottle carry stress.

Table 10.2 Design requirements for drink containers	
Function	■ Drink container
Constraints	■ Must contain the pressure of dissolved CO ₂ safely ■ Must be moldable ■ Must be transparent or translucent ■ Must be recyclable
Objective	■ Minimize embodied energy per unit capacity ■ Minimize the cost per unit capacity
Free variables	■ Choice of wall thickness ■ Choice of material

where ρ is the density of the bottle material and CO_2 is the carbon footprint of the material per kilogram. The best choice of material is one with the smallest value of the index:

$$M_1 = (CO_2)\rho/\sigma_y. \tag{10.3}$$

Cost, of course, is an issue in a product like this. The cost of the bottle material per unit area is calculated as above, simply replacing the carbon footprint, CO_2 kg/kg, with the material cost, C_m \$/kg, giving the index:

$$M_2 = C_m\rho/\sigma_y. \tag{10.4}$$

Which index should we use? We have a trade-off issue here.

Table 10.3 lists the properties of transparent materials that can be molded. The last two columns give the values of the two indices, the first for CO_2 , the second for cost. The trade-off between them is plotted as Fig. 10.4. PET and polylactide (PLA) lie on the trade-off surface, making them better choices than any of the others. PET is the least expensive; PLA has the lowest carbon footprint.

Postscript: Today most carbonated drink containers are made of PET. They are likely to remain so. Economic benefits outweigh environmental benefits until the eco-gain is a lot larger than that suggested by this case study. The costs and uncertainties of changing from a material that is well tried and attractive to consumers, and that has an established recycling infrastructure, to another that is less well tried, more expensive, and more difficult to recycle are too great to accept.

Table 10.3 Glass and transparent thermoplastics and their properties^a

Material (transparent thermoplastics)	Density (kg/m ³)	Yield strength (MPa)	CO ₂ footprint (kg/kg)	Price (\$/kg)	Index M_1 (kg/MJ)	Index M_2 (\$/MJ)
Cellulose acetate	990	26	3.4	5.5	129	209
Polyethylene	950	23	2.8	1.6	116	66
Poly lactide	1300	63	2.8	3.2	58	66
Polyurethane	1200	46	3.2	4.7	84	123
Polystyrene	1000	34	2.5	2.2	74	65
Polymethyl methacrylate	1200	62	4.9	4.3	95	83
Polyethylene terephthalate	1300	52	2.7	1.4	68	35
Polycarbonate	1200	62	4.8	3.4	93	66
Soda-lime glass	2500	33	0.76	1.5	58	114

^aData from Appendix A, Tables A2 and A3, and from Appendix B, Table B2.

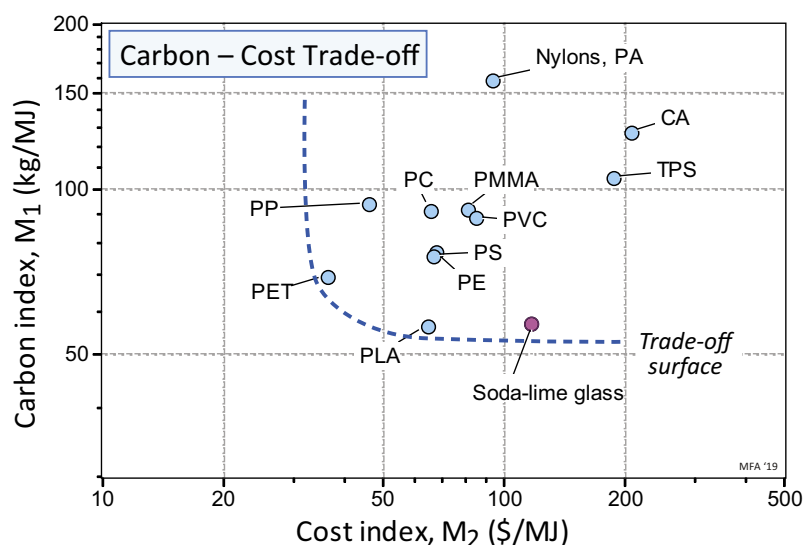


FIGURE 10.4 A carbonated drink bottle must support an internal pressure. The trade-off plot for moldable transparent or translucent polymers shows that polyethylene terephthalate (PET) is the cheapest, and polylactide (PLA) has the lowest carbon emission.

Example: saving material in drink containers. The working pressure in a Pepsi bottle is about 5 atm (0.5 MPa, 75 psi). The bottle has a diameter $2r = 64$ mm and is made of PET. How thick must the wall of the bottle be to carry this pressure safely? Use a safety factor S of 2. The yield strength of PET is approximately 52 MPa. The wall thickness of Pepsi bottles is about 0.7 mm. Is there scope for making them thinner while retaining a safety factor of 2?

Answer. The required wall thickness t is:

$$t = S \frac{pr}{\sigma_y} = 2 \times \frac{0.5 \times 0.032}{52} = 0.00062 \text{ m} = 0.62 \text{ mm.}$$

No. It seems that Pepsi bottles already use as little PET as is practical.

10.4 Structural materials for buildings

The built environment is the largest of all consumers of materials. The aggregated embodied energy and carbon associated with it is enormous; we are talking GJ and tonnes now, not MJ and kg. Here, the functional unit we need is “energy or carbon per unit area (m^2) of floor space.”

The initial embodied energy of a building is the energy used to acquire raw materials, manufacture building products, transport them, and assemble them on-site. In the past, the “use energy” of a building for heating, cooling, and lighting quickly exceeded that of its construction, but the great advances in energy-efficient design have changed that—a “zero-carbon” house is one with zero net emissions during use, but it does not include the energy and carbon to build it in the first place. Architects and civil engineers now must look more closely at the embodied energies of the materials they use. What are they?

A local realtor (estate agent) advertises “an exceptional property boasting wood construction with delightful concrete patio and exquisite steel-framed roof that has to be seen to be appreciated.” Filter out the noise and you are left with three words: wood, concrete, steel. These are, indeed, the principal materials of the structure of buildings. The structure is just one of the material-intensive parts of a building. It provides the frame that carries the self-weight and working loads, resists the wind forces, and, where needed, supports the dynamic loads of earthquakes. The structure is clad and insulated by the envelope. It gives weather protection, thermal insulation, radiation screening, and acoustic separation and provides the color, texture, and short-term durability of the building. The building has to work, and that needs services: internal dividers; supply of water, gas, and electricity; heating and cooling; ventilation; control of light and sound; and disposal of waste. And there is the interior: the materials that the occupants see, use, and feel: the floor and wall coverings, furnishings,

Table 10.4 Embodied energy per square meter: concrete frame building

	Embodied energy (GJ/m ²)	Percent of total
Site work	0.29	6
Structure	0.93	22
Envelope	1.26	28
Services	1.11	23
Construction	0.37	7
Interior finishes	0.30	14
Total	4.52	100

and fittings. The four different groups—structure, envelope, services, interior—have different primary functions. All four are material hungry (Table 10.4).

The initial embodied energy per unit area of floor space of a building depends on what it is made of and where. An approximate figure is 4.5 GJ/m²; we'll get more specific in a moment. Fig. 10.5 shows where it goes: about a quarter each into the materials of the structure, those of the envelope, those of the services, and those of site preparation, building work, and interior lumped together. They differ most in the choice of materials for the structure.

Table 10.5 compares the structural embodied energy per square meter of steel-framed, a reinforced-concrete, and a wood-framed building. The wood frame has the lowest value, the steel frame the highest: it is 72% more energy intensive than wood and 33% more so than concrete.

Postscript: If wood is the most energy-efficient material for building structures, why are not all buildings made of wood? As always, there are other considerations.

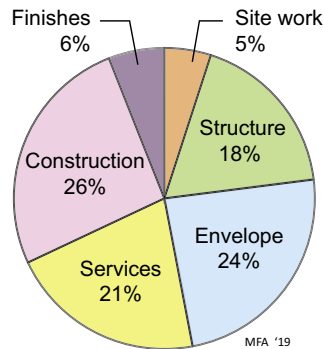


FIGURE 10.5 The relative energies associated with the construction of a typical three-story office building.

Table 10.5 Embodied energy/m ² of alternative building structures		
Structural type	Mass of materials (kg/m ²)	Embodied energy ^a (GJ/m ²)
Steel frame	86, steel 625, concrete	1.2
Reinforced concrete frame	68, steel 900, concrete	0.9
Wood frame	80, timber	0.67

^aCole and Kernan (1996).³ Underground parking, add 0.26 GJ/m².

There is the obvious constraint of scale: wood is economic for small structures, but for buildings above four floors in height, steel and concrete are usually more practical. There is availability: where wood is plentiful (Maine, USA, for instance) wood is widely used, but elsewhere (London, UK) it is not. There are issues of recyclability: steel is easily recycled, but reusing wood or concrete at end of life is more difficult. The trade-off between all of these determines the final choice. With the increased focus on carbon reductions, the balance is shifting. Wood-framed buildings with up to 18 floors exist or are under construction in a number of cities.

Newsclip: “Tall wood-framed buildings are sprouting up across Canada.”

Developers embrace new designs to reduce the heavy carbon footprint of concrete and steel in construction as the urgency of the battle to combat climate change grows.

The Canadian Press, January 20, 2019

10.5 Initial and recurring embodied energy of buildings

The life cycle of a building is more complex than that of a short-lived product. Five aspects of life require energy and have associated release of carbon to the atmosphere:

- the materials
- site preparation and construction
- recurring upgrades of the interior and envelope during life
- heating, cooling, lighting, ventilation, and power during life
- demolition and disposal at end of life

³Cole, R.J. and Kernan, P.C. (1996) “Life-cycle energy use in office buildings,” *Building and Environment*, Vol. 31, No. 4, pp. 307–317.

Consider, as an example, the life energy per square meter of a small office block with a 60-year design life. Such a building, if built of reinforced concrete, uses about 970 kg of material per square meter of floor area (Table 10.5) and has a total embodied energy of materials of about 4.5 GJ/m² (Table 10.4). The structure of the building is designed to last for its full life. The envelope, interior, and services, for functional or aesthetic reasons, might be upgraded every 15 years, replacing interior walls, floors, doors, finishes, and mechanical and electrical services. Estimates for the energy of upgrades vary between 2 and 4 GJ/m²—we shall take 3 GJ/m², incurred once every 15 years, as typical. There will be three such upgrades over the 60-year life of the building, absorbing 9 GJ/m², twice as much as the initial embodied energy.

Environmental design in the building industry since the 1990s has focused on reducing the operating energy, which is now much lower than it used to be: values of 0.5–0.9 GJ/m² per year are now possible. We will use the value 0.7 GJ/m² per year, giving a 60-year use energy of 42 GJ/m². If the building materials are transported 500 km to the site by a heavy goods vehicle (a 40-tonne truck), consuming 0.82 MJ/tonne·km (Appendix B, Table B9), the transport energy is $0.82 \times 500 \times 0.97 = 0.41$ GJ/m². Finally, at end of life the building is demolished. Estimate of energy for demolition and transport to landfill: 0.13 GJ/m².

These data are plotted in Fig. 10.6A. The significant terms are the initial embodied energy (8% of the total), the recurring embodied energy (16%), and the energy of use (74%). Fig. 10.6B shows how the energy accumulates over life. The use energy exceeds the initial embodied energy after only about 7 years, despite the extremely efficient heat conservation implied by the value we chose for the use energy per year. The recurring embodied energy first appears after 15 years, and steps up each subsequent 15-year interval.

Postscript: Some constructors now offer “carbon-neutral” or “zero-energy” housing, meaning zero use energy. Heat is captured by passive solar heating:

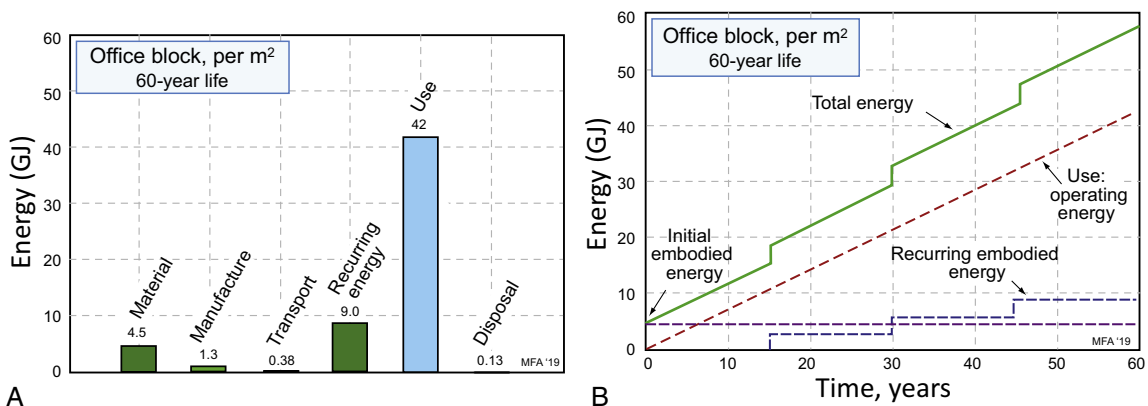


FIGURE 10.6 (A) The contributions to the life energy per square meter of floor area of a three-story office building with a life of 60 years. (B) The way the energy evolves over the life.

high-heat-capacity walls oriented so they are warmed by sunlight during the winter day and release heat into the house at night. A large roof overhang shades the walls when the sun is high in the summer. Cooling is provided by airflow and the use of the underlying earth as a heat sink. Electrical power is derived from solar panels.

10.6 Heating and cooling (1): refrigeration

Heating and cooling are among the most energy-gobbling, CO₂-belching things we do. Refrigerators, freezers, and air conditioners keep things cold. Central heating, ovens, and kilns keep things hot. For all of these appliances it is the use phase of life that contributes most to energy consumption and emissions. Some, like refrigerators and incubators, aim to hold temperatures constant over long periods of time. Others, like ovens and kilns, heat up and cool down every time they are used, zigzagging up and down in temperature over the span of a few hours. Commercial office space lies somewhere in between, heated or cooled during the day but not at night or on the weekend. The best choice of material to minimize heat loss depends on the form of the use cycle.

Refrigerators. An A*-rated refrigerator with a capacity of 330 L (0.33 m³, 12 ft³) consumes 175 kWh/year, weighs 72 kg, and costs \$470 (€420). The fridge is made in Germany and imported to the United Kingdom by 55-tonne (eight-axle) truck. Table 10.6 lists the approximate bill of materials. Fig. 10.7 shows the energy and carbon fingerprint of the fridge, assuming a life of 10 years, at the end of which the fridge is recycled. Not surprisingly, the use phase of life dominates both.

Table 10.6 An approximate bill of materials ⁴ for a 330-L refrigerator			
Component	Material	Process	Mass (kg)
Frame, outer skin, motor, compressor parts	Carbon steel	Roll formed	56
Inner liner	Polyurethane	Molded	11
Clear doors and shelves	Polycarbonate	Molded	0.6
Wire shelves	Stainless steel	Wire-drawn	0.8
Insulation	Polyurethane foam	Foam molded	1
Electrical conductors	Copper	Wire-drawn	1.9
Condenser, evaporator	Aluminum	Tube-drawn	2.3

⁴<https://www.hunker.com/12609170/what-are-fridges-made-of>.

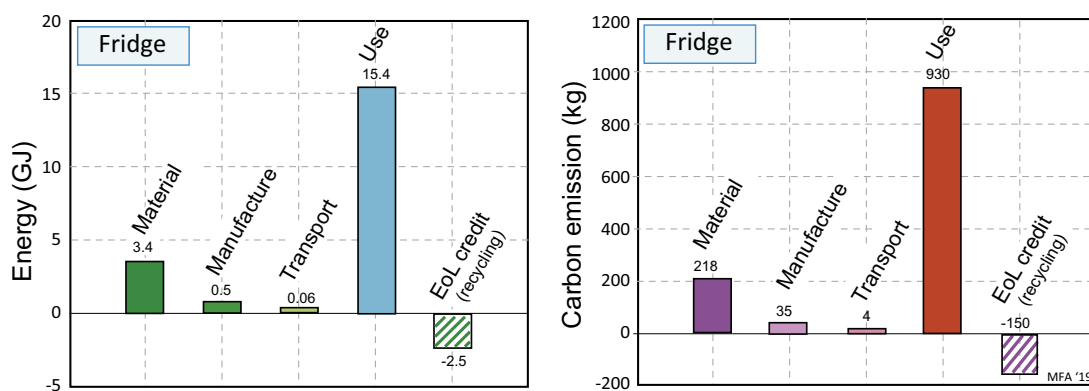


FIGURE 10.7 The eco-audit of the fridge, using a world-average energy mix for the electric power of the use phase. A low-carbon mix (that of Norway, largely hydroelectric, for example) leaves the use energy unchanged but greatly reduces the use carbon. EoL, end of life.

The eco-objective for a fridge is to minimize energy and emissions per year per cubic meter of cold space. The energy loss per unit area of fridge wall, q joules/m² per second, is:

$$q = -\lambda \frac{T_i - T_o}{t}, \quad (10.5)$$

where λ is the thermal conductivity of the insulation between the outer skin and the liner, T_i and T_o are the inside and outside temperatures of the fridge, and t is the thickness of the insulation. The energy loss is minimized by selecting the insulation with the lowest thermal conductivity and making it as thick as possible. But the thicker it is, the more it will cost. The maker of the fridge will want the foam that costs the least per unit volume. Fig. 10.8 compares conductivity and price of foams per unit volume. The best choices are circled.

Postscript: Refrigerators can be hazardous. A recent tragedy—the Grenfell tower-block fire in London, UK, in June 2017—started in a refrigerator. What can be done to reduce the risk? Fires start at electrical faults and spread if the materials surrounding the fault are combustible. Table 10.7 ranks the flammability of common polymer foams used for fridge insulation. Risk of fire is greatly reduced by choosing a phenolic rather than a polyurethane foam for the insulation.

10.7 Heating and cooling (2): materials for passive solar heating

There are many ways to capture solar energy for home heating: solar cells, liquid-filled heat exchangers, solid heat reservoirs, and even phase-change materials. The simplest of these is the heat-storing wall: a thick wall, the outer surface of which is

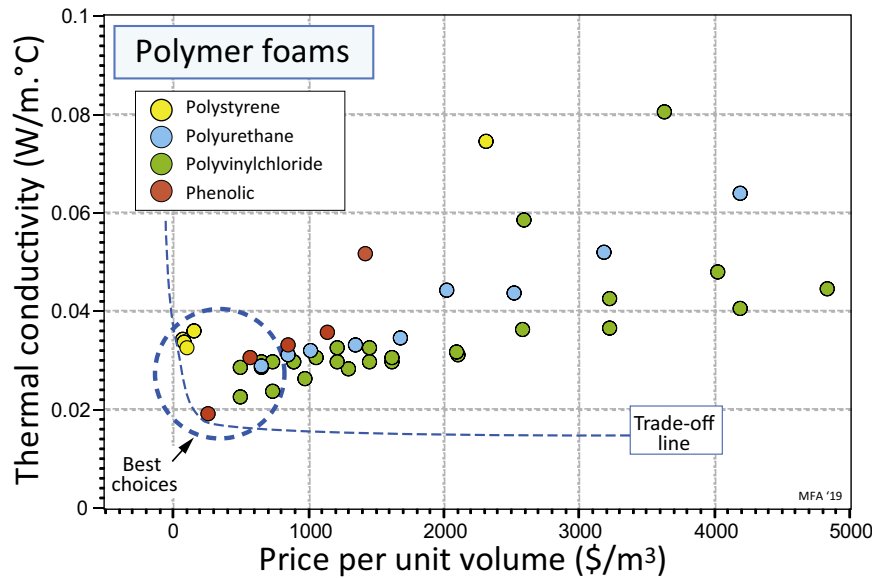


FIGURE 10.8 The thermal conductivity and price of polymeric insulating foams.

Table 10.7

The flammability of polymer foams

Foam material	Flammability rating
Polystyrene	Highly flammable
Polyurethane	Highly flammable
Poly(vinyl chloride)	Self-extinguishing
Phenolic	Nonflammable

heated by direct sunshine during the day and from which heat is extracted at night by blowing air over its inner surface (Fig. 10.9). An essential of such a scheme is that the time constant for heat flow through the wall be about 12 hours; then the wall first warms on the inner surface roughly 12 hours after the sun first warms the outer one, giving out at night what it took in during the day. We will suppose that, for architectural reasons, the wall must not be more than 400 mm thick. What materials maximize the thermal energy captured by the wall while retaining a heat-diffusion time of up to 12 hours? Table 10.8 summarizes the requirements.

The heat content, Q , per unit area of wall, when heated through a temperature interval, ΔT , is:

$$Q = w\rho C_p \Delta T, \quad (10.6)$$

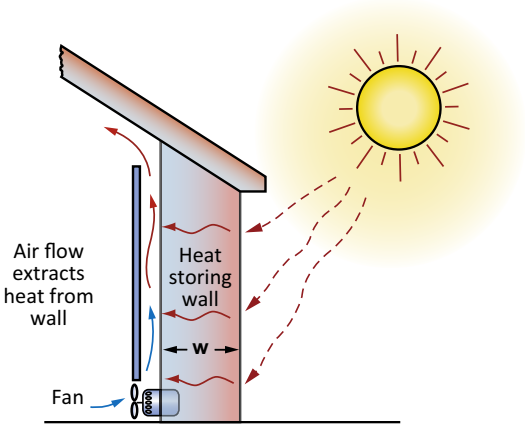


FIGURE 10.9 A heat-storing wall. The sun heats the wall during the day; heat is extracted from it at night.

Table 10.8	Design requirements for materials for passive solar heating
Function	Heat-storing medium
Constraint	Heat-diffusion time through wall, $t \approx 12$ hours Wall thickness ≤ 0.4 m Adequate working temperature, $T_{\max} > 100^\circ\text{C}$
Objective	Maximize thermal energy stored per unit material cost
Free variables	Wall thickness, w Choice of material

where w is the wall thickness, and ρC_p is the volumetric specific heat (the density ρ times the specific heat C_p). When one surface of a cold wall is exposed to heat, a thermal front diffuses into it. The distance the thermal front diffuses in time t is:

$$x \approx \sqrt{2at}, \tag{10.7}$$

where a is the thermal diffusivity. Equating this to the wall thickness w and eliminating w between these two equations gives:

$$Q = \sqrt{2t\Delta T}a^{1/2}\rho C_p, \tag{10.8}$$

or, using the fact that $a = \lambda/\rho C_p$ where λ is the thermal conductivity,

$$Q = \sqrt{2t\Delta T}\left(\frac{\lambda}{a^{1/2}}\right).$$

The heat capacity of the wall is maximized by choosing material with a high value of:

$$M = \frac{\lambda}{a^{1/2}}. \quad (10.9)$$

The restriction on thickness w requires (from Eq. 10.7) that:

$$a \leq \frac{w^2}{2t},$$

with $w \leq 0.4$ m and $t = 12$ hours (4.3×10^4 s), defines an upper limit for the thermal diffusivity:

$$a \leq 1.9 \times 10^{-6} \text{ m}^2/\text{s}. \quad (10.10)$$

Fig. 10.10 shows these conditions plotted onto the $\lambda - a$ chart introduced in the last chapter as Fig. 9.6. It identifies the group of materials listed in Table 10.9: they

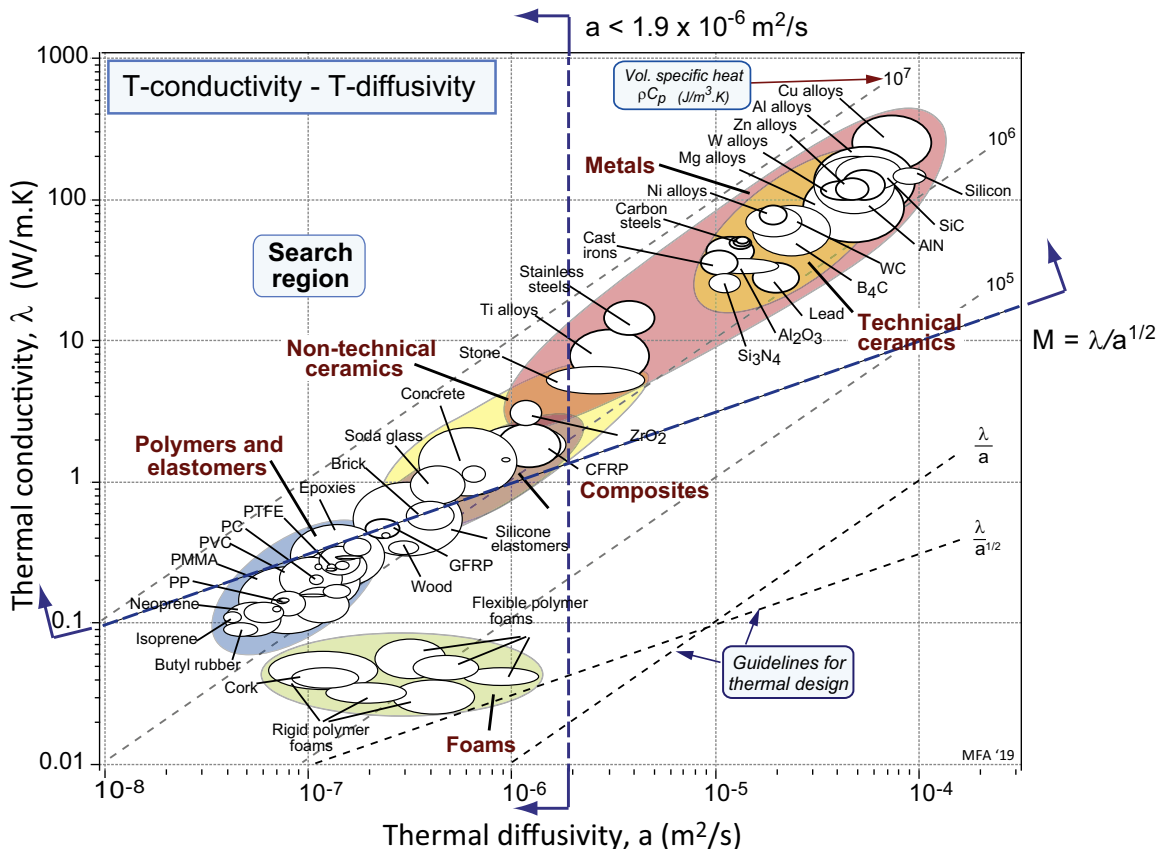


FIGURE 10.10 Materials for heat-storing walls. Concrete, brick, stone, and glass are practical choices.

Table 10.9 Materials for passive solar heat storage^a

Material	$M_1 = \lambda/a^{1/2}$ ($\text{W}\cdot\text{s}^{1/2}/\text{m}\cdot^2\text{K}$)	Approx. Cost $\$/\text{m}^3$	Comment
Concrete	2.2×10^3	120	The best choice—good performance at minimum cost
Stone	3.5×10^3	1200	Better performance than concrete because specific heat is greater, but more expensive
Brick	10^3	2000	Less good than concrete
Glass	1.6×10^3	3750	Useful—part of the wall could be glass

^aData from Appendix A, Tables A1, A5, and A6.

maximize M while meeting the constraint on wall thickness. Solids are good; porous materials and foams (often used in walls) are not.

Postscript: All this is fine, but what about the cost? If this scheme is to be used for housing, cost is an important consideration. The approximate costs per unit volume, calculated from the data of Appendix A, Table A2, are listed in the table—it points to the selection of concrete, with stone and brick as alternatives.

10.8 Heating and cooling (3): kilns and cyclic heating

When space is held at constant temperature, energy loss is minimized by choosing materials with as low a thermal conductivity λ as possible. But when space is heated and cooled in a cyclic way, the choice of material for insulation is more subtle. Take, as a generic example, the oven or kiln sketched in Fig. 10.11—we will refer to it as “the kiln.” The design requirements are listed in Table 10.10.

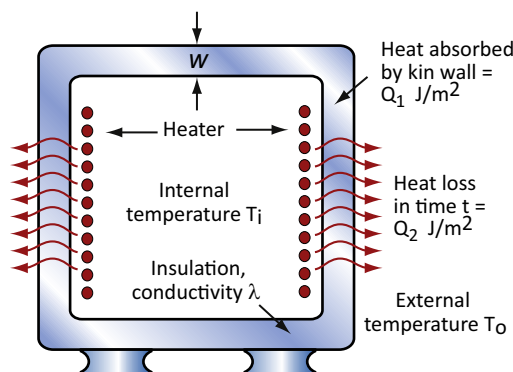


FIGURE 10.11 A heated chamber with heat loss by conduction through the insulation.

Table 10.10 Design requirements for kiln wall

Function	Thermal insulation for kiln (cyclic heating and cooling)
Constraint	Maximum operating temperature 1000°C Upper limit on kiln–wall thickness for space reasons
Objectives	Minimize energy consumed in a heat–cool cycle
Free variables	Kiln wall thickness, w Choice of material

When the kiln is fired, the internal temperature rises from ambient, T_o , to the operating temperature, T_i , where it is held for the firing time t . The energy consumed in one firing has two contributions. The first is the heat absorbed by the kiln wall in raising it to T_i . Per unit area, it is:

$$Q_1 = C_p \rho w \left(\frac{T_i - T_o}{2} \right), \quad (10.11)$$

where C_p is the specific heat of the wall per unit mass (so $C_p \rho$ is the specific heat per unit volume) and w is the insulation wall thickness; $(T_i - T_o)/2$ is just the average temperature of the kiln wall. Q_1 is minimized by choosing a wall material with a low heat capacity $C_p \rho$ and by making it as thin as possible. The second contribution is the heat lost by conduction through the wall, Q_2 , per unit area. It is given by the first law of heat flow. If held for time t it is:

$$Q_2 = -\lambda \frac{dT}{dx} t = \lambda \frac{(T_i - T_o)}{w} t. \quad (10.12)$$

It is minimized by choosing a wall material with a low thermal conductivity λ and by making the wall as thick as possible.

The total energy consumed per unit area is the sum of these two:

$$Q = Q_1 + Q_2 = \frac{C_p \rho w \Delta T}{2} + \frac{\lambda \Delta T}{w} t, \quad (10.13)$$

where $\Delta T = (T_i - T_o)$. Consider first the limits when the wall thickness w is fixed. When the heating cycle is short, the first term dominates and the best choice of material is that with the lowest volumetric heat capacity $C_p \rho$. When instead the heating cycle is long, the second term dominates and the best choice of material is that with the smallest thermal conductivity, λ .

A wall that is too thin loses much energy by conduction, but little is used to heat the wall itself. One that is too thick does the opposite. There is an optimum thickness, which we find by differentiating Eq. (10.13) with respect to wall thickness w and equating the result to zero, giving:

$$w = \left(\frac{2\lambda t}{C_p \rho} \right)^{1/2} = (2\lambda t)^{1/2}, \quad (10.14)$$

where $a = \lambda / \rho C_p$ is the thermal diffusivity of the wall material. The quantity $(2at)^{1/2}$ has dimensions of length and is a measure of the distance heat can diffuse in time t . Substituting Eq. (10.14) back into Eq. (10.13) to eliminate w gives:

$$Q = (\lambda C_p \rho)^{1/2} \Delta T (2t)^{1/2}. \quad (10.15)$$

This is minimized by choosing a material with the lowest value of the quantity:

$$M = (\lambda C_p \rho)^{1/2} = \frac{\lambda}{a^{1/2}}. \quad (10.16)$$

Fig. 10.12 shows the $\lambda - a$ chart of Chapter 9, Fig. 9.6, expanded to include more materials that are good thermal insulators. All three of the criteria we have derived—minimizing $C_p \rho$, λ , and $(\lambda C_p \rho)^{1/2}$ —can be plotted on it; the “guidelines”

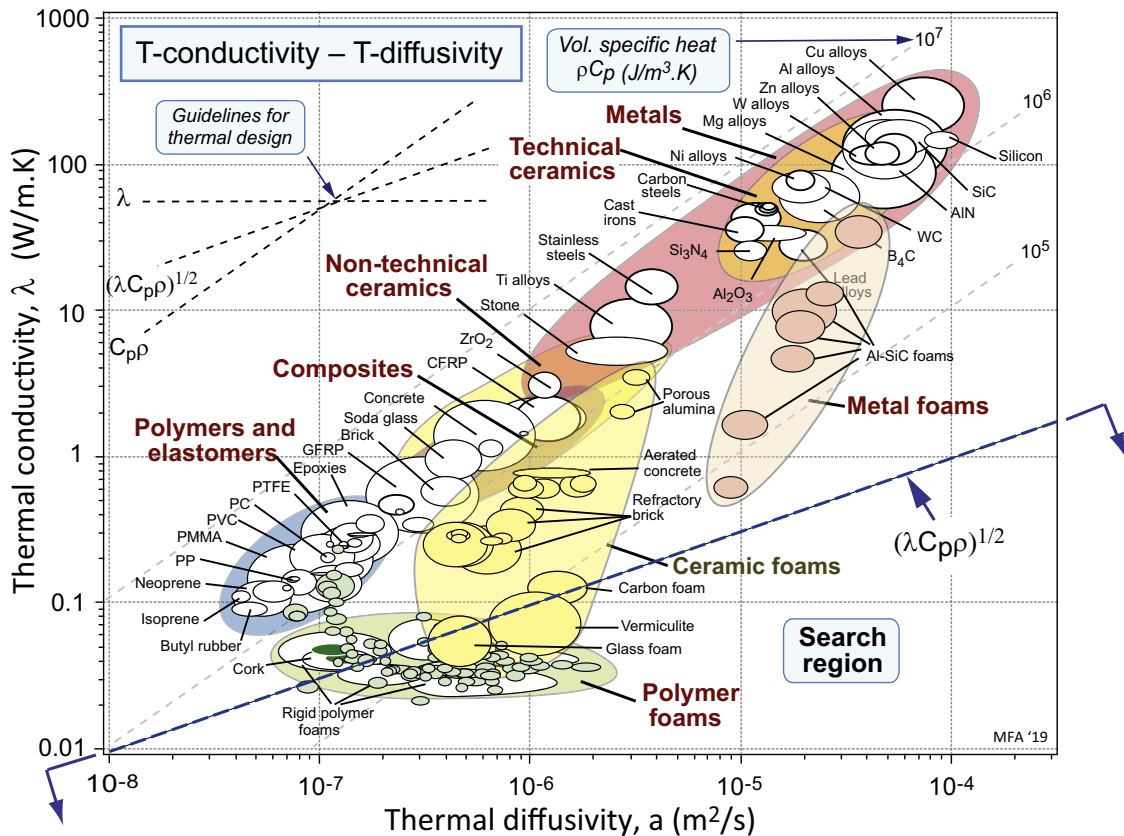


FIGURE 10.12 The thermal conductivity–thermal diffusivity chart with contours of volumetric specific heat. It guides selection for efficient thermal design.

show the slopes. For long heating times it is λ we wish to minimize and the best choices are the materials at the bottom of the chart: polymeric foams or, if the temperature T_i is too high for them, foamed glass, vermiculite, or carbon. But if we are free to adjust the wall thickness to the optimum value of Eq. (10.14), the quantity we wish to minimize is $(\lambda C_p \rho)^{1/2}$. A selection line with this slope is plotted on the figure. The best choices are the same as before, but now the performance of vermiculite, foamed glass, and foamed carbon is almost as good as that of the best polymer foams. Here the limitation of the hard-copy charts becomes apparent: there is not enough room to show a large number of specialized materials such as refractory bricks and concretes. The limitation is overcome by the computer-based methods mentioned in Chapter 9, allowing a search over a much greater number of materials.

Postscript: It is not generally appreciated that, in the thermal cycle of an efficiently designed kiln, as much energy goes into heating up the kiln itself as is lost by thermal conduction to the outside environment. It is a mistake to make kiln walls too thick; a little is saved in reduced conduction loss, but more is lost in the greater heat capacity of the kiln itself.

That, too, is the reason that foams are good: they have a low thermal conductivity λ and a low volumetric heat capacity $C_p \rho$, giving them particularly attractive values of $(\lambda C_p \rho)^{1/2}$. Centrally heated houses in which the heat is turned off at night suffer a cycle like that of the kiln. Here (because T_i is lower) the best choice is a polymeric foam, cork, or fiberglass (which has thermal properties like those of foams). But as this case study shows, turning the heat off at night doesn't save as much as you think, because you have to supply the heat capacity of the walls in the morning.

10.9 Transport (1): introduction

Transport by sea, road, rail, and air together account for 32% of all the energy we use and 34% of all the emissions we generate (Fig. 2.5). Cars contribute a large part of both. The primary eco-objective in car design is to provide mobility at minimum environmental impact, which we will measure here by the CO₂ rating in grams per kilometer. The audits of Chapter 8 confirmed what we already knew: that the energy consumed during the life phase of a car exceeds that of all the other phases put together. If we are going to reduce it, we first need to know how it depends on vehicle mass and propulsion system.

Modeling. Where does the energy go? Energy in transport is dissipated in three ways:

- as the energy needed to accelerate the vehicle up to its cruising speed, giving it kinetic energy that is lost on braking;
- as drag exerted by the air or water through which it is passing; and
- as rolling friction in bearings and the contact between wheels and road.

Imagine (following MacKay, 2008) that a vehicle with mass m accelerates to a cruising velocity v acquiring kinetic energy:

$$E_{ke} = \frac{1}{2}mv^2. \quad (10.17)$$

It continues over a distance d for a time d/v before braking, losing this kinetic energy as heat and dissipating energy per unit time (power) of:

$$\frac{dE_{ke}}{dt} \approx \frac{E_{ke}}{d/v} = \frac{1}{2} \frac{mv^3}{d}. \quad (10.18)$$

While cruising, the vehicle drags behind it a column of air with a cross-section proportional to its frontal area A . The column created in time t has a volume $c_d A v t$, where c_d is the drag coefficient, typically about 0.3 for a car and 0.4 for a bus or truck. This column has a mass $\rho_{air} c_d A v t$ and it moves with velocity v so the kinetic energy imparted to the air is:

$$E_{drag} = \frac{1}{2} m_{air} v^2 = \frac{1}{2} \rho_{air} c_d A v^3 t, \quad (10.19)$$

where ρ_{air} is the density of air. The drag is the rate of change of this energy with time (= power):

$$\frac{dE_{drag}}{dt} = \frac{1}{2} \rho_{air} c_d A v^3. \quad (10.20)$$

If this cycle is repeated over and over again, the power dissipated is the sum of these two:

$$\text{Power} = \frac{1}{2} \left(\frac{m}{d} + \rho_{air} c_d A \right) v^3. \quad (10.21)$$

Rolling resistance adds another small term that is proportional to the mass, which we will ignore.

The first term in the brackets is proportional to the mass m of the vehicle and inversely proportional to the distance d it moves between stops. The second depends only on the frontal area A and the drag coefficient c_d . Thus, for short-haul, stop-go, or city driving, the way to save fuel is to make the vehicle as light as possible. For long-haul, steady cruising, or motorway driving, mass is less important than minimizing drag, making frontal area A and drag coefficient c_d of greater importance.

Fuel consumption and emissions are minimized by reducing all of these power-dissipating mechanisms: recuperative braking to reuse kinetic energy, low-drag shapes to reduce air drag, low-rolling-resistance tires to reduce road-surface losses, and low overall mass because of its direct link to fuel consumption. The data for

the combined⁵ energy consumption and carbon rating of Fig. 6.14 show a near-linear dependence of both on mass, meaning that, in normal use, it is the kinetic energy term, Eq. (10.21), that dominates. Thus, design to minimize the energy and CO₂ of vehicle use must focus on material selection to minimize mass. The resulting energy and CO₂ emission per kilogram per kilometer for a typical 1000-kg vehicle are listed in Table 10.11. These are the penalty in energy and carbon for a 1-kg increase in mass of the car, or the savings in both if the car mass is reduced by 1 kg.

10.10 Transport crash barriers—matching material to purpose

Barriers to protect driver and passengers of road vehicles are of two types: those that are static—the central divider of a freeway, for instance—and those that move—the bumper of the vehicle itself (Fig. 10.13). The static type lines tens of thousands of miles of road. Once in place, they consume almost no energy, create no CO₂, and last a long time. The bumper, by contrast, is part of the vehicle; it adds to its mass and thus to its fuel consumption. Fig. 10.14 shows the eco-audit for each. Material and process dominate the eco-life of the static barrier; use dominates that of the bumper. If eco-design is the objective, the criteria for selecting materials for the two sorts of barrier differ: minimizing material embodied energy for the first, minimizing mass for the second.

In an impact, a barrier is loaded in bending (Fig. 10.13). The function of the barrier is to transfer load from the point of impact to the support structure, where reaction from the foundation or from crush elements in the vehicle support or absorb it. To do this the material of the barrier must have high strength, σ_y , be

Table 10.11 The energy and CO₂ penalty of 1 kg mass increase for cars

Fuel type	Energy (MJ/km · kg) (<i>m</i> = 1000 kg)	CO ₂ (kg/km · kg) (<i>m</i> = 1000 kg)
Petrol	2.1×10^{-3}	1.4×10^{-4}
Diesel	1.6×10^{-3}	1.2×10^{-4}
LPG	2.2×10^{-3}	0.98×10^{-4}
Hybrid	1.3×10^{-3}	0.92×10^{-4}

LPG, *liquid propane gas*.

⁵“Combined energy consumption” means that for a typical mix of urban and extra-urban driving.

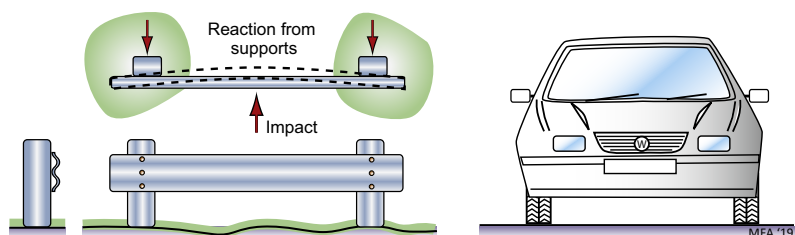


FIGURE 10.13 Two crash barriers, one static, the other—the bumper of the car—attached to something that moves. In action both are loaded in bending. The criteria for material selection for each differ.

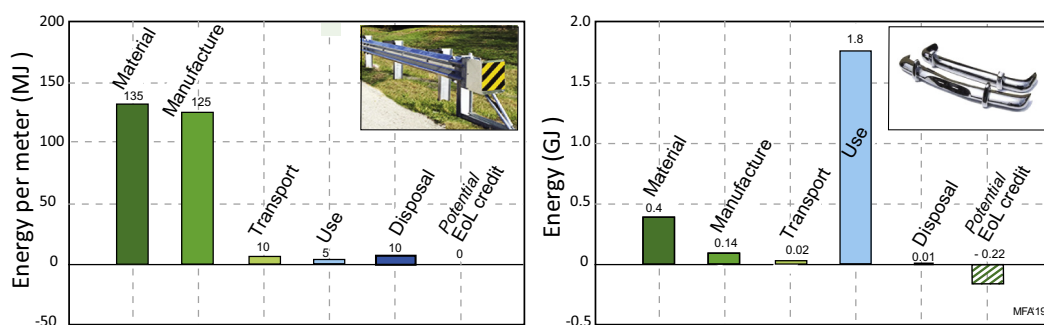


FIGURE 10.14 Eco-audits for the crash barriers, one static, the other mobile. EoL, end of life.

adequately tough, and be able to be recycled. That for the static barrier must meet these constraints with minimum embodied energy as the objective, since this will reduce the overall life energy most effectively. We know from Chapter 9, Table 9.3, that this means materials with low values of the index

$$M_1 = \frac{H_m \rho}{\sigma_y^{2/3}}, \quad (10.22)$$

where ρ is the density and H_m is the embodied energy per kilogram of material. For the car bumper it is mass, not embodied energy, that is the problem. If we change the objective to that of minimum mass, we require materials with low values of the index

$$M_2 = \frac{\rho}{\sigma_y^{2/3}}. \quad (10.23)$$

Fig. 10.15 guides the selection for static barriers. It shows that embodied energy for a given bending-load-bearing capacity (Eq. 10.22) is minimized by making the barrier from steel or cast iron or wood; nothing else comes close. The second figure (Fig. 10.16) guides selection for the mobile barrier: it is a bar chart of Eq. (10.23). Here, CFRP (carbon-fiber-reinforced polymer) excels in its bending strength per

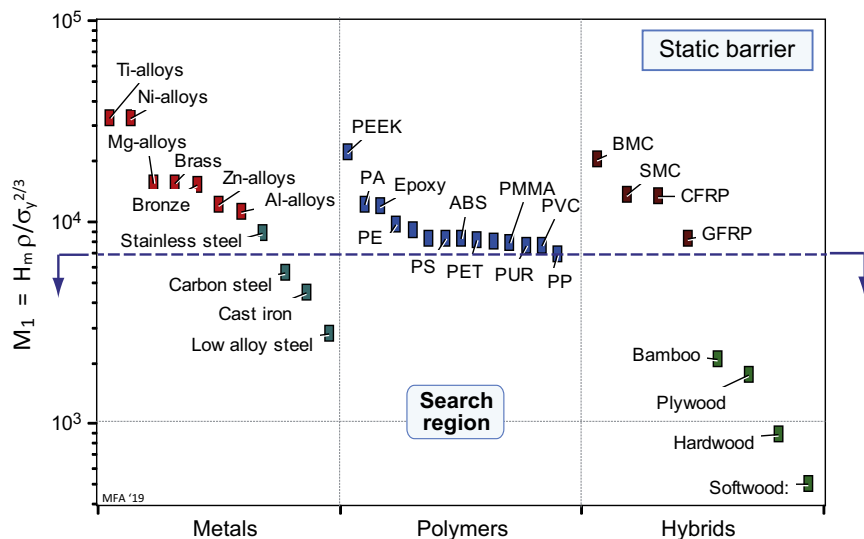


FIGURE 10.15 Material choice for the static barrier is guided by the embodied energy per unit of bending strength, $H_m \rho / \sigma_y^{2/3}$, here in units of $(\text{MJ}/\text{m}^3)/\text{MPa}^{2/3}$. Cast irons, carbon steels, or wood are the best choices.

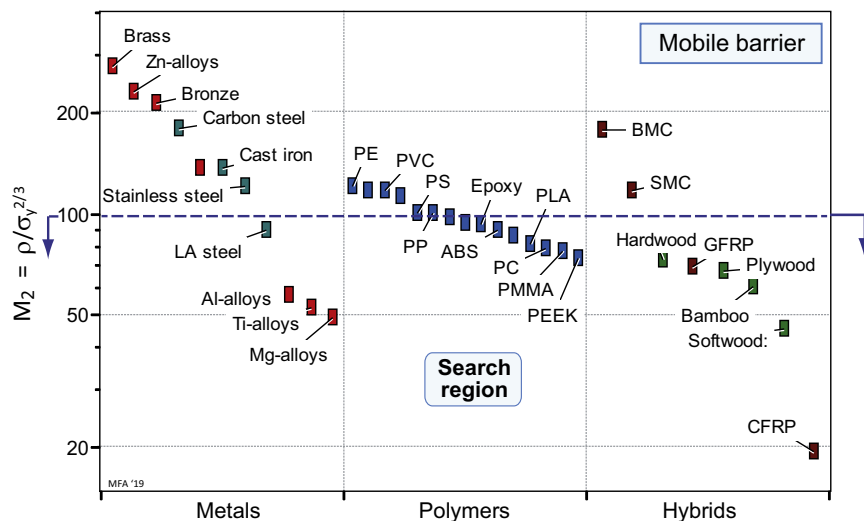


FIGURE 10.16 Material choice for the mobile barrier is guided by the mass per unit of bending strength, $\rho / \sigma_y^{2/3}$, here in units of $(\text{kg}/\text{m}^3)/\text{MPa}^{2/3}$. Carbon-fiber-reinforced polymer (CFRP) and light alloys offer the best performance. Many polymers now perform better than steel.

unit mass, but it is not recyclable. Heavier, but recyclable, are alloys of magnesium, titanium, and aluminum. Significantly, a number of thermoplastic polymers now perform better than steel. It is these that are used for the bumpers of most modern cars.

Postscript: Roadside crash barriers have a profile like that shown on the left of Fig. 10.13. The “3”-shaped profile increases the second moment of area of the cross-section, and through this the bending stiffness and strength. This is an example of combining material choice and section shape. More on shape in a moment.

10.11 Transport (3): materials for lightweight structures

Mass matters when things have to move. There are three strategies for making them lighter, while still meeting the requirements of stiffness and strength, captured by the three words: “material,” “shape,” and “configuration.”

Material. Loading on a component can be decomposed into three modes: axial tension or compression, bending, and torsion. It is the second two—bending and torsion—that usually create the biggest challenges. Indices for selection materials that best support a given mode are listed in Table 9.3. As an example, consider selecting a material for a light, strong beam. The relevant index is:

$$M = \rho / \sigma_y^{2/3}. \quad (10.24a)$$

Materials with the lowest (best) value of this index are found by plotting it onto a material property chart with density ρ and strength σ_y as axes, or by direct evaluation. The first option is illustrated in Fig. 10.17, a copy of Fig. 9.3. Using the guideline corresponding to the index M , a line with the same slope is plotted on the chart and moved to the left until a small number of materials remain above it. In this (extreme) example, there is only one. It is CFRP. The same operation can be done digitally using the software described in Section 9.6, with a much larger number of materials to choose from.

Shape. Fig. 10.18A shows a simple square-section beam. A solid square section is a bad choice for a light beam. When a beam is loaded in bending, most of the load is carried by the outer elements; the elements along the central neutral axis of bending carry no load at all. You get more bending strength and stiffness by redistributing the material to where it works best, far from the neutral axis (Fig. 10.18B). The gain is measured by the shape factor Φ , a dimensionless measure of the efficiency of use of material. I-sections and hollow-tube sections can have large values of Φ . The maximum shape factor depends on the material. Two shape factors are needed, one for stiffness-limited design (symbol Φ^e) and one for strength-limited design (symbol Φ^f). The index for a light, strong beam equation does not allow for differences in shape. The modified index

$$M = \rho / (\Phi^f \sigma_y)^{2/3}, \quad (10.24b)$$

includes it.

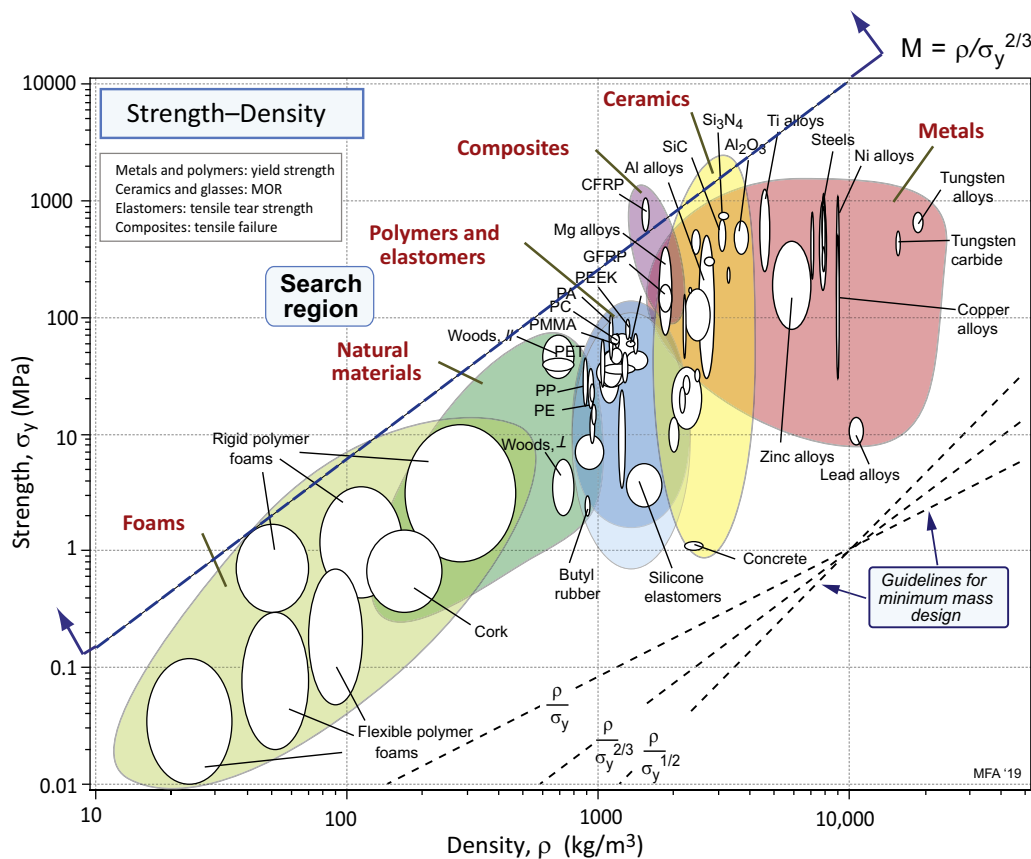


FIGURE 10.17 The strength–density chart with a selection line isolating the lightest materials for a strong beam (MOR, Modulus of Rupture).

How much weight is saved by shaping? The materials 1020 steel, 6061 aluminum, glass-fiber-reinforced polymer, and hardwood have different potentials to be shaped. Table 10.12 lists the values for the properties that enter Eq. (10.24). The ratio of the two for a given material, $(1/\Phi^f)^{2/3}$, is a measure of the mass savings made possible by shaping. It is listed in the last column of the table.

Configuration. Can we do better still? To do so we have to think not only of shape but also of configuration. A beam is a configuration. There are others. One is a pin-jointed truss (Fig. 10.18C). The truss can support bending loads, but none of its members is loaded in bending: all are loaded in either simple tension or simple compression. The best material for the lightest truss is that with the smallest value of ρ/σ_y , the same as that for simple tension and compression. Not surprising—it is because the truss turns bending loads into axial loads, and in so doing it allows further weight savings.

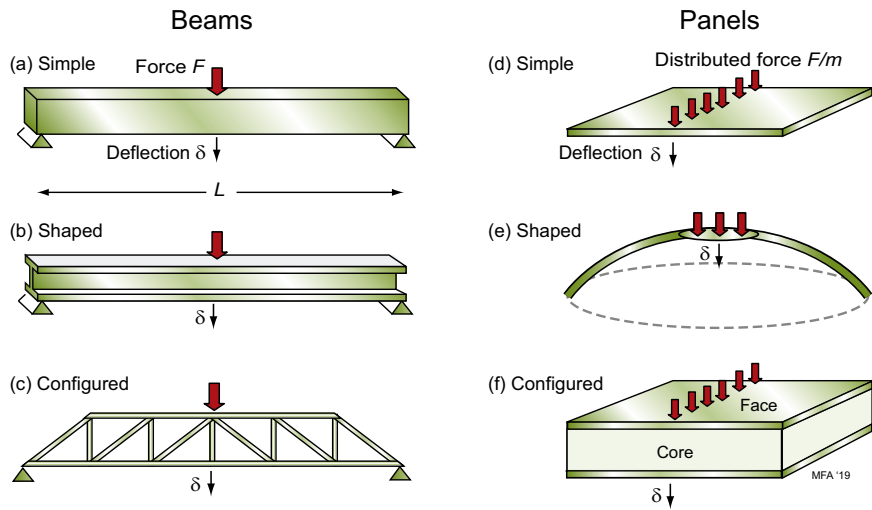


FIGURE 10.18 Examples of (A, D) simple, (B, E) shaped, and (C, F) configured beams and panels.

Table 10.12 Properties of materials for lightweight structures						
Material	Shape not included				Shape included, with weight savings	
	ρ (kg/m ³)	σ_y (MPa)	$\frac{\rho}{\sigma_y^{2/3}}$	Φ^f	$\frac{\rho}{(\Phi^f \sigma_y)^{2/3}}$	$\frac{m_2}{m_1} = \frac{1}{(\Phi^f)^{2/3}}$
1020 steel, normalized	7850	330	164	13	30	0.18
6061-T4 aluminum	2710	113	116	10	25	0.22
GFRP SMC, 30% glass	1770	83	93	6	28	0.30
Wood (oak), along grain	760	40	65	3	31	0.48

GFRP, glass-fiber-reinforced polymer.

Shells and sandwiches. Fig. 10.18D shows a simple flat panel. Panels bend easily; they can be made stiffer and stronger by giving them a doubly curved shape, creating a shell [Fig. 10.18E]. A shell, when loaded in bending, is stiffer and stronger than a flat or singly curved sheet of the same thickness because any attempt to bend it creates membrane stresses: tensile or compressive stress in the plane of the sheet. Sheets support tension or compression much better than they support bending, so the double curvature gives another way to save weight without loss of stiffness and strength.

Here, too, configuration can help. A sandwich panel (Fig. 10.18F) combines two materials, one for the faces, another for the core. When the panel is loaded in bending the faces carry most of the load. The role of the core is to separate them, moving them away from the central plane and increasing their moment of area.

Postscript: CFRP is the material of choice for Formula 1 cars, super-yachts, and efficient aircraft. But there is more to it than that. The best performance is achieved by a combination of material and shape. CFRP offers exceptional stiffness and strength per unit mass; making it into a doubly curved shell adds shape stiffness, further enhancing performance. Yet higher efficiency is possible by making the shell from a sandwich with CFRP faces separated by a high-performance foam core, combining both shape and configuration. Details of how shape factors are measured and why the maximum value is material dependent can be found in Chapters 10 and 11 of the first reference in “Further reading” at the end of this chapter, which also deals with sandwich structures.

10.12 Transport (4): material substitution for eco-efficient design

Making cars lighter means replacing heavy steel and cast iron components with those made of lighter materials: light alloys based on aluminum, magnesium, or titanium; polymers; and composites reinforced by glass or carbon fibers. All these materials have a greater embodied energy and carbon footprint than steel, introducing another sort of trade-off: that between the competing energy demands and the emissions of different life phases. There is a net savings of energy and CO₂ only if that saved in the use phase by reducing mass exceeds that invested in the material phase as extra embodied energy.

All very straightforward. Well, not quite. As explained in Chapter 9, Section 9.2, material substitution in a component that performs a mechanical function requires that the component be rescaled to have the same stiffness or strength (whichever is design limiting) as the original. In making the substitution, the mass of the component changes both because the density of the new material differs from that of the old and because the scaling changes the volume of material that is used. Steel has a larger density than, say, aluminum, but it is also stiffer and stronger. We must scale in such a way that the function is maintained. The scaling rules are known: they are given by material indices developed in Chapter 9, Table 9.3. Here is how to use them.

Consider the replacement of the pressed steel bumper set of a car, described in Section 10.10, by one made of a lighter material. The function and mass scaling of the bumper were described earlier: it is a beam of given bending strength with a mass, for a given bending strength, that scales as $\rho / \sigma_y^{2/3}$, where ρ is the density and σ_y is the yield strength of the material of which it is made. The bumper set,

made of a lighter material (subscript “1”) is lighter than the one made of steel (subscript “o”) by the ratio:

$$\frac{m_1}{m_0} = \frac{\rho_1/\sigma_{y,1}^{2/3}}{\rho_o/\sigma_{y,o}^{2/3}}. \quad (10.25)$$

The use emissions of the new bumper are lower than those of the old one because it is lighter. If we assume that fuel consumption and associated emissions are proportional to vehicle weight, the use emissions are reduced by the same factor as the mass.

The carbon footprint of the lighter bumper differs from that of the steel one by the ratio:

$$\frac{\text{Carbon, material 1}}{\text{Carbon, material 2}} = \frac{(\text{CO}_2)_1 \rho_1 / \sigma_{y,1}^{2/3}}{(\text{CO}_2)_o \rho_o / \sigma_{y,o}^{2/3}}, \quad (10.26)$$

where (CO_2) is the carbon footprint per kilogram of the material of the bumper (Appendix B, Table B2).

The trade-off between material carbon and use carbon is plotted in Fig. 10.19. Mild steel, the material of the original bumper, lies at the point (1,1). The materials in the gray-shaded segment are bad choices: if these are chosen, the lifetime carbon emissions are greater than those of the original steel bumper. The best choices are the materials closest to the trade-off line: low-alloy steel and CFRP. A number of polymers perform better than steel (they lie closer to the trade-off line), among them polypropylene, polycarbonate, and acrylonitrile butadiene styrene.

Before a final decision is reached, it is helpful to have a feeling for the likely change in cost. Assuming again that fuel consumption scales with mass, the ratio of fuel cost over life of the new bumper differs from that of the steel one by the same ratio as the mass (Eq. 10.25 again). The ratio of the material cost of the new bumper to that of the old is given by Eq. (10.26), with the material carbon footprint/kg, (CO_2) , replaced by the material price/kg, C_m :

$$\frac{\text{Cost, material 1}}{\text{Cost, material 2}} = \frac{C_{m,1} \rho_1 / \sigma_{y,1}^{2/3}}{C_{m,o} \rho_o / \sigma_{y,o}^{2/3}}. \quad (10.27)$$

Cost, of course, has other contributions than just that of the materials. Part of the cost of a component is that of manufacture. If it takes longer to shape, join, and finish with the new material than with the old, there is an additional cost penalty, so the material cost of Eq. (10.27) must be regarded as approximate only.

With this simplifying approximation, the cost trade-off (following the pattern used for carbon) appears as in Fig. 10.20. Titanium alloys lie well inside the “No win” zone. Low-alloy steels, magnesium alloys, aluminum alloys, and CFRP are the most attractive from an economic point. Significantly, polypropylene and PET now look like attractive substitutes, economical and, at the same time, easy to shape. The bumpers of many small cars today are made of polypropylene.

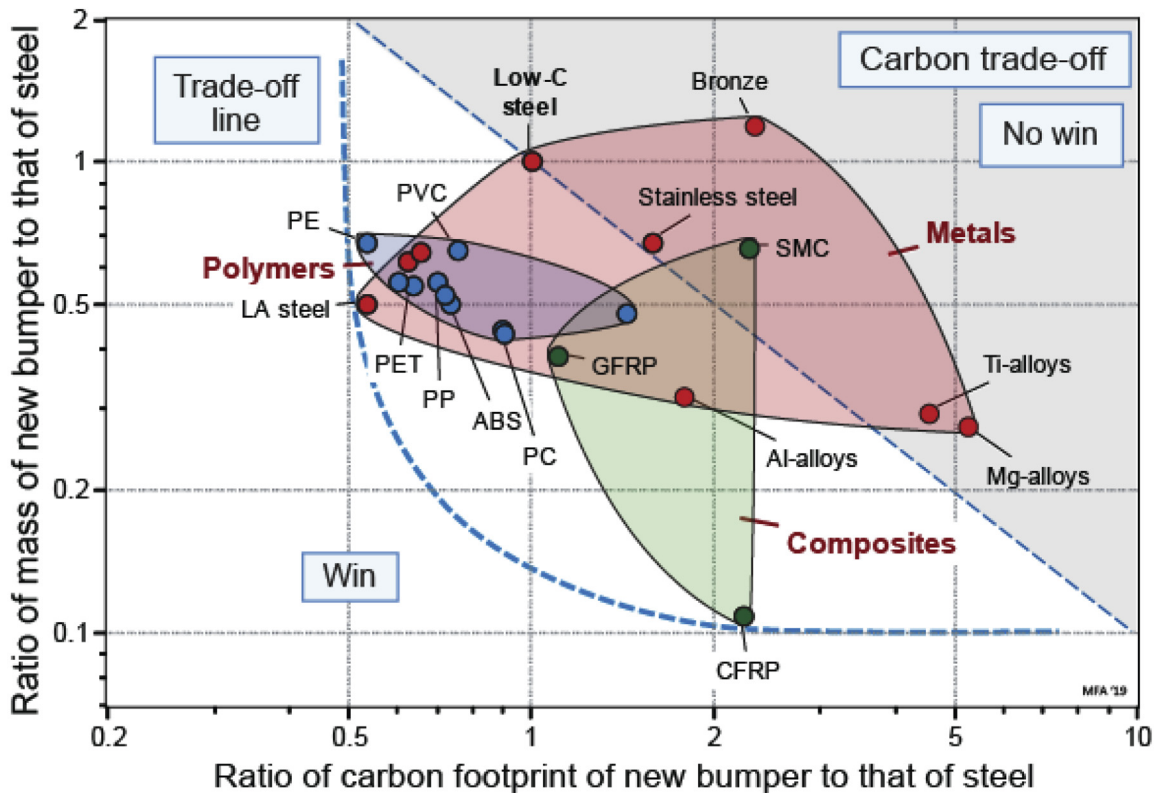


FIGURE 10.19 Trade-off between material carbon footprint and use carbon footprint for the bumper.

Postscript: We have focused here on primary mass savings that material substitution brings. In reality the savings are—or can be—larger, because the lighter vehicle requires less heavy suspension, lighter tires, and less powerful brakes, allowing a secondary mass savings. In current practice, however, aluminum cars are not much lighter than the steel ones they replace because manufacturers tend to load them with more extras (such as air conditioning and double glazing), putting mass back on.

Newsclip: Ultra-efficient transport. “Volkswagen reveals its 313 mpg hybrid.”

The Sunday Times, February 2011

A fuel efficiency of 313 mpg is 1 L/100 km. Automakers claims for fuel efficiency seldom quite match the experience of the purchaser of the vehicle. But even allowing for that, this car will still go five times farther on a liter of fuel than any ordinary one. How has Volkswagen achieved it? Aerodynamics, low-loss tires, a tiny

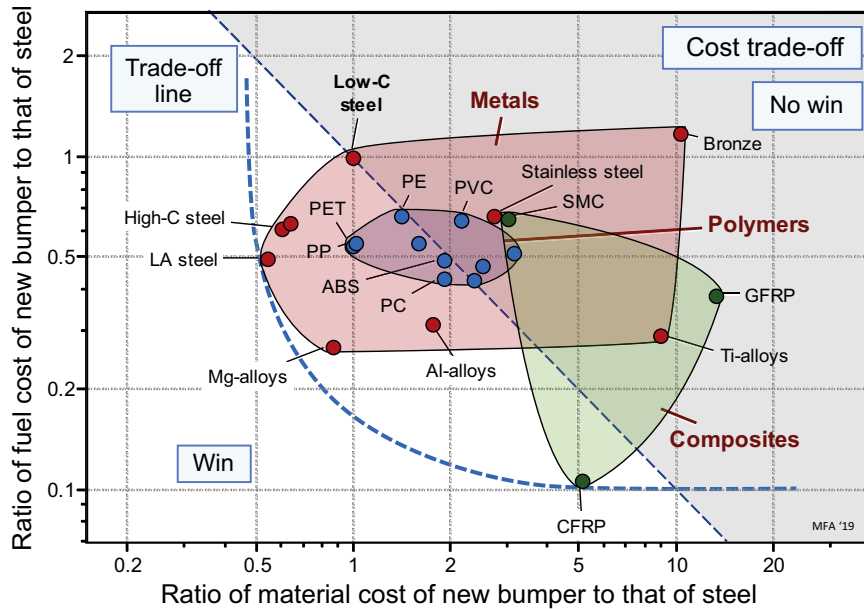


FIGURE 10.20 Trade-off between material cost and fuel cost for the bumper.

800-cc diesel power source, hybrid technology, and, above all, low mass—795 kg all up, about half the weight of a mid-sized car, achieved through the use of CFRP monocoque construction.

As we have seen, the energy consumption and carbon emission of ordinary cars are dominated by the use phase. But if you divide these by 5 (as VW claims to do) and use materials with four times greater embodied energy for the structure (CFRP), the balance changes. The dominant contribution to life energy and emissions now becomes that of the materials, changing the criteria for material selection.

Example: weight savings by substituting. All-CFRP construction allows great savings of mass. Both stiffness and strength are central to the mechanical design of the body shell of cars. Assume for the moment that in lightweight design it is strength that is the first concern. If it were stiffness instead, there would be little point in replacing mild steel with high-strength low-alloy steel to save mass, as some carmakers are doing, since both materials have the same modulus and density. Assume that bending, not tension, is the critical mode of loading (as it usually is). Given the material properties listed in the table below, by what factor can mass be reduced if an all-steel shell is replaced by an all-CFRP shell of the same strength?

Material	Density (kg/m ³)	Yield strength (MPa)	$\rho / \sigma_y^{2/3}$
Mild steel	7850	310	171
CFRP	1550	540	23

Answer. The mass savings in material substitution is measured by the index $\rho / \sigma_y^{2/3}$ (Table 9.3). The last column lists the value of this index for steel and CFRP. The CFRP structure has the potential to be lighter by a factor of about 7. All that assumes that the composite shell is as efficiently designed as present-day steel shells and that the problems of joining it to the power train do not add mass.

10.13 **Summary and conclusions**

Rational selection of materials to meet environmental objectives starts by identifying the phase of product life that causes greatest concern: production, manufacture, transport, use, or disposal. Dealing with all of these requires data not only for the obvious eco-attributes (energy, emissions, toxicity, ability to be recycled, and the like) but also for mechanical, thermal, electrical, and chemical properties. If material production is the phase of concern, selection is based on minimizing embodied energy and associated emissions, and using as little material as possible. But if it is the use phase that is of concern, selection is based instead on light weight or excellence measured by thermal or electrical properties. These define the objective; the idea is to minimize them while meeting all the other constraints of the design: adequate stiffness, strength, durability, and the like.

Almost always there is more than one objective and, almost always, they conflict. Conflicting objectives arise in more than one way. One is the obvious tension between eco-objectives and cost, illustrated both in Chapter 8 and here. Then trade-off methods offer a way forward, provided a cash value can be assigned to the eco-objective, something that is not always easy. Another conflict is that between the energy demands and the emissions of different phases of life: the conflict between increased embodied energy of the material and reduced energy of use, for example. Trade-off methods work well for this type of problem too, because both energies can be quantified. The case studies of this chapter illustrate how such problems are tackled. The following exercises present more.

10.14 **Further reading**

Ashby, M.F. (2017) “Materials selection in mechanical design”, 5th edition, Butterworth Heinemann, Oxford, UK. (*A text that develops the ideas presented here in more depth, including the derivation of material indices, a discussion of shape factors and light weight structures.*)

- Ashby, M.F., Shercliff, H.R., and Cebon, D. (2019) "Materials: engineering, science, processing and design", 4th edition, Butterworth Heinemann, Oxford, UK. (*An elementary text introducing materials through material property charts, and developing the selection methods through case studies.*)
- Caceres, C.H. (2007), "Economical and environmental factors in light alloys automotive applications", Metallurgical and Materials Transactions, A. (*An analysis of the cost-mass trade-off for cars.*)
- Calladine, C.R. (1983) "Theory of shell structures", Cambridge University Press, Cambridge UK. (*A comprehensive text developing the mechanics of shell structures.*)
- Carlsaw, H.S. and Jaeger, J.C. (1959) "Conduction of heat in solids", 2nd edition, Oxford University Press, Oxford, UK. (*A classic text dealing with heat flow in solid materials.*)
- Hollman, J.P. (1981) "Heat transfer", 5th Edition, McGraw Hill, New York. (*An introduction to problems of heat flow.*)
- MacKay, D.J.C. (2008) "Sustainable energy – without the hot air", Department of Physics, Cambridge University, Cambridge, UK. www.withouthotair.com/ (*MacKay brings common sense into the discussion of energy use.*)
- Young, W.C., Budynas, R. and Sadegh, A. (2011) "Roark's formulas for stress and strain", 8th edition, McGraw-Hill, New York (*A "Yellow pages" for results for calculations of stress and strain in loaded components.*)

10.15 Exercises

E10.1. Allowing for recycled content. The drink containers of Fig. 10.2 of the text were compared on the basis of carbon emissions per liter of fluid contained, using data for virgin material (carbon footprint $\text{CO}_{2,m}$). In practice, all but the last use recycled materials to different degrees. If the carbon footprint for recycled material is $\text{CO}_{2,rc}$ and the fraction of recycle in the material of the container is f_{rc} , by what factor are the carbon emissions per liter reduced?

E10.2. Drink containers with recycled content. The materials of the drink containers of Fig. 10.2 use recycled materials to different degrees. How does the ranking of Table 10.1 of the text change if the contribution of recycling is included? To do so, multiply the carbon footprint per liter in the last column of the table by the correction factor derived in Exercise E10.1:

$$1 - f_{rc} \left(1 - \frac{\text{CO}_{2,rc}}{\text{CO}_{2,m}} \right),$$

where f_{rc} is the recycled fraction in current supply, $\text{CO}_{2,m}$ is the embodied energy for primary material production, and $\text{CO}_{2,rc}$ is that for recycling of the material. The table lists values for the drink-container materials.

Container type	Material	CO ₂ footprint (CO _{2,m}) (kg/kg)	Recycled CO ₂ * (CO _{2,rc}) (kg/kg)	Recycled fraction* in current supply
PET 500 mL	PET	2.7	1.5	0.21
PE 1 L milk	High-density PE	2.8	0.94	0.084
Glass 750 mL	Soda glass	0.76	0.53	0.24
Al 440 mL	5000 series Al alloy	12	2.6	0.43
Steel 440 mL	Plain carbon steel	2.3	0.67	0.42
Laminate	Cardboard/PE/Alu/PP	3.55	2 (?)	0

* From Appendix B, Tables B2 and B7.
PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene.

The recycling of laminated containers is controversial. These websites have useful information.

<https://www.tetrapak.com/sustainability/environmental-impact/a-value-chain-approach/carton-co2e-footprint>

<https://treadingmyownpath.com/2014/09/11/why-tetra-paks-arent-green-even-though-theyre-recyclable/>

E10.3. Estimating embodied energies for building structures. The table lists the approximate masses of structural materials per square meter of floor space required for a steel-framed building and a wood-framed building. Assuming that the steel has 100% recycled content and that the concrete and wood have 0%, what are the embodied energies per square meter for the two alternative frames? To evaluate these, take data for the embodied energies of 100% recycled carbon steel and for virgin concrete and softwood from Appendix B, Tables B7 and B2. Compare the resulting energies per square meter with the values from the life-cycle assessment quoted in Table 10.5 of the text.

Structural type	Mass of material (kg/m ²)
Steel frame	86 steel 625 concrete
Wood frame	80 timber

E10.4. Estimating embodied energies for building envelopes. The cladding of a framed building provides an envelope to give protection against the elements. It must do so while imposing as little additional dead load on the structural frame as possible, and it should enhance the architectural

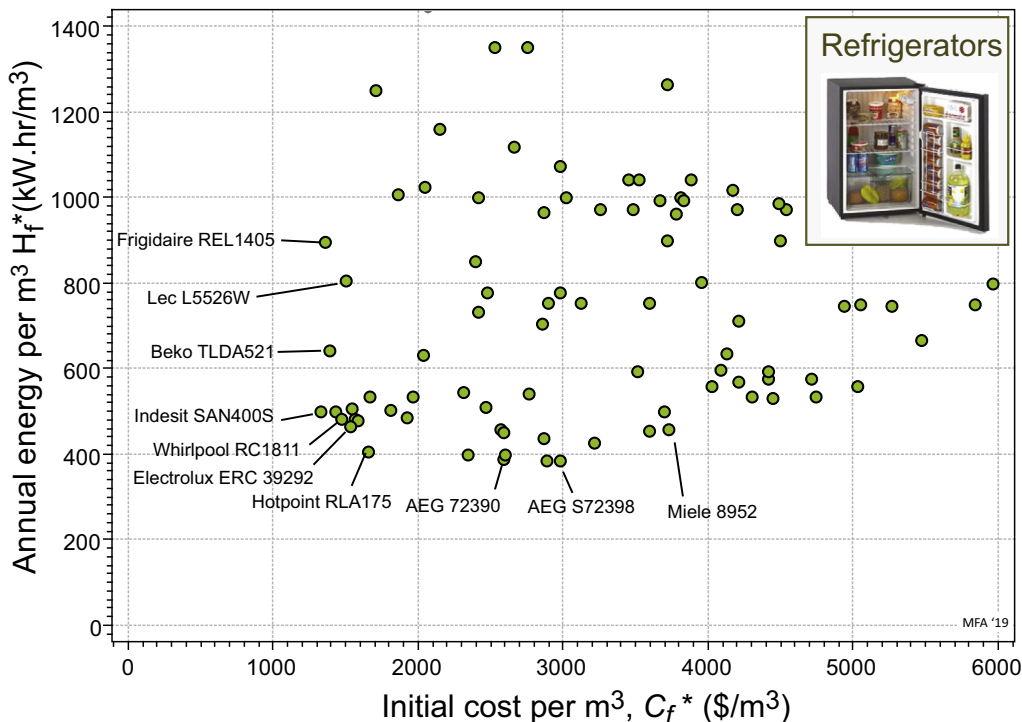
concept and appearance of the building. Alternative cladding materials include 1.5-mm aluminum sheet, 10-mm plywood, or 3-mm poly(vinyl chloride). Use data from Appendix A, Table A2, and Appendix B, Tables B5 and B7, to estimate the embodied energy per square meter of clad surface using each of these materials. Assume that the aluminum has a recycled content of 50% and that the other two materials have none.

E10.5. Thermal mass. Define specific heat. What are its usual units? How would you calculate the specific heat per unit volume from the specific heat per unit mass? If you wanted to select a material for a compact heat-storing device, which of the two would you use as a criterion of choice?

E10.6. Exchange constants (1). The figure shows data for refrigerators: the initial cost per cubic meter (C_f , $\$/\text{m}^3$) and the energy consumption per cubic meter (H_f , MJ/m^3). The life cost of refrigerated space per cubic meter is measured by the penalty function:

$$Z = C_f + \alpha_e H_f t,$$

where α_e , the exchange constant linking energy to cost, is the cost of energy per kilowatt-hour and t is the service life of the fridge in years. The objective is to select the fridge that minimizes Z .



- (a) Sketch a trade-off line onto the figure, identifying the nondominated fridges.
- (b) Construct a set of contours for values of the penalty function $Z = \$1000/\text{m}^3$, $Z = \$2000/\text{m}^3$, and $Z = \$3000/\text{m}^3$ assuming the cost of electrical power to be US\$0.1/kWh. Hence, identify the fridge that has the lowest life cost.

E10.7. Exchange constants (2). In a far-away land, fridges cost the same as they do in Exercise 10.6 and they last just as long (10 years), but electrical energy costs 10 times more—that is, it costs \$1/kWh. Make a copy of the trade-off plot for fridges in Exercise 10.6. Sketch in the trade-off line. Now construct a new set of penalty lines on it, using \$1/kWh for the exchange constant, α_e . If you had to choose just one fridge to use in this unfortunate land, which would it be? (In another 20 years, this may be us.)

E10.8. Minimizing energy loss in thermal cycles. You are asked to design a large heated workspace in an exceptionally cold climate, making it as eco-friendly as possible by attaching polystyrene foam insulation to the inside wall. Polystyrene foam has a density of 110 kg/m^3 , a specific heat capacity of $1200 \text{ J/kg}\cdot\text{K}$, and a thermal conductivity of $0.03 \text{ W/m}\cdot\text{K}$. The space will be heated during the day (12 hours) but not at night. What is the optimum thickness, w , of foam to minimize the energy loss?

E10.9. Using property charts. The crash barriers of Fig. 9.3 require materials that are strong and light (mobile barrier, index $\rho/\sigma_y^{2/3}$) and strong and with low carbon footprint (static barrier, index $(\text{CO}_2)\rho/\sigma_y^{2/3}$). Use the charts for strength and density (Fig. 9.3) and strength and carbon/ m^3 (Fig. 9.5) to select materials for each of the barriers. Create a line with the slope chosen from the guidelines. Position your selection line to include one metal above the selection line for each. Reject ceramics and glass on the grounds of brittleness. List what you find for each barrier.

E10.10. Light materials for energy-efficient vehicles (1). The makers of a small electric car wish to make bumpers out of a molded thermoplastic. Which index is the one to guide this selection if the aim is to maximize the range for a given battery storage capacity? Plot it on the appropriate chart from the set shown as Figs. 9.2–9.6, and make a selection.

E10.11. Light materials for energy-efficient vehicles (2). Car bumpers used to be made of steel. Most cars now have extruded aluminum or glass-reinforced polymer bumpers. Both materials have a much higher embodied energy than steel. Take the weight of a steel bumper set to be 20 kg and that of an aluminum one to be 14 kg. Take the energy consumption per tonne per kilometer for a family car to be $2.1 \text{ MJ/tonne}\cdot\text{km}$.

Work out how much energy is saved by changing the bumper set of a 1000-kg car from steel to aluminum, over an assumed life of 200,000 km.

Calculate whether the switch from virgin steel to virgin aluminum has saved energy over life. The embodied energies of steel and aluminum are listed in Appendix B, Table B2. Ignore the differences in energy in manufacturing the two bumpers—it is small.

Repeat the calculation for bumpers made from 100% recycled steel and aluminum. Appendix B, Table B7, gives the necessary energies.

The switch from steel to aluminum increases the price of the car by \$60. The energy content of gasoline is 35 MJ/L. Fuel cost depends on country; it varies at present between \$0.5/L and \$2/L. Using a pump price of \$1 for gasoline, work out whether, over the 200,000 km life, it is cheaper to have the aluminum bumper or the steel one.

Renewable materials, natural materials

CONTENTS

- 11.1 Introduction and synopsis
- 11.2 Natural materials
- 11.3 Biopolymers
- 11.4 Fibers, natural and synthetic
- 11.5 Bio-based composites
- 11.6 Summary and conclusions
- 11.7 Further reading
- 11.8 Appendix: Natural materials—brief portraits
- 11.9 Exercises



¹ <https://www.homebuilding.co.uk/67k-straw-bale-low-cost-self-build/>

² <https://www.shutterstock.com/image-photo/classic-adobe-house-169471826> from Shutterstock.com.

³ <https://www.shutterstock.com/image-photo/06282018-normandy-france-old-traditional-cottage-1137789233> from Shutterstock.com.

⁴ <https://www.shutterstock.com/image-photo/luxury-home-15796114> from Shutterstock.com.

11.1 Introduction and synopsis

For millennia, human needs for shelter, clothing, and tools for agriculture and for defense were met by renewable materials: materials that can be re-created in both quantity and quality at the same rate at which they are used. Most were derived from the biosphere. Their substitution by synthetic materials is comparatively recent. In architecture, steel displaced wood around 1900. From 1950, polymers replaced natural materials and even metals in market after market, taking the place of steel in cars, paper and glass in packaging, and wood in furniture. By 2000, synthetic fibers had finally displaced those of nature—cotton, jute, and wool—as the dominant fiber type. The replacement of the renewable materials of nature with those extracted or synthesized from nonrenewable resources is virtually complete (see Fig. 1.2 of Chapter 1).

Extracting and synthesizing materials takes energy, consumes resources, and leaves a legacy of waste. Nature makes materials, too, but nature harvests its own energy and consumes only resources that it can reprocess back into their original form. And natural materials are renewable, meaning that they offer a (potentially) inexhaustible supply. Is it time to reassess the wider use of the biosphere as a provider of materials?

It is a question that is attracting increasing attention from architects, product designers, and governments, but before you can propose ways to do it, you need to know what resources you've got. What do the properties of bio-materials look like? This chapter is about bio-based materials, those that are in part or in whole derived from renewable resources. To put them in perspective, we will compare their properties to those of competing synthetics.

It is important to accept one inescapable characteristic of natural materials: their properties are variable. Metals, polymers, and fibers can be produced to meet closely defined specs. Woods and natural fibers cannot; their properties depend on the growing conditions and vary from batch to batch and year to year. Does this matter? Fig. 11.1 shows the distribution of values of a property, one carefully controlled, the

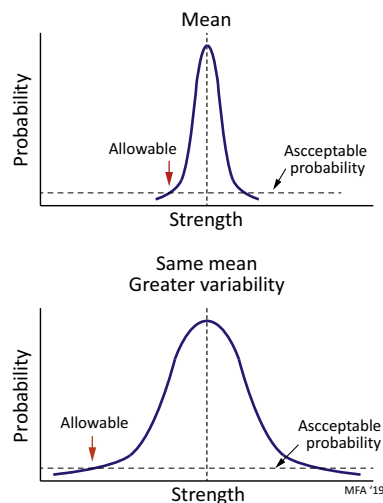


FIGURE 11.1 The effect of variability on the allowable design strength.

other more variable. The mean values are the same for both. But engineers don't design products based on the mean, but on an "allowable"—a value of the property that can be guaranteed with known probability. The figure illustrates that a wide variability gives a low allowable, sometimes far below the value of the mean.

Newsclip: "The dawning of the (new) Timber Age: wood will overtake steel & concrete in architecture."

There has been an aesthetic shift in modern architecture that's moving away from cold materials. Innovations in engineered timber and changes in building codes are making it possible to build skyscrapers almost entirely of wood.

Easternwhitepine.org, February 1, 2016

11.2 Natural materials

Fig. 11.2 shows a hierarchy of natural structural materials. Some come from vegetable sources, some from animal, some from mineral. How "renewable" are they? Take wood as an example. Provided the total tree stock is constant, such that wood is harvested at the same rate as it is grown, wood could be seen as a renewable. Today some softwoods are managed sustainably, but globally wood is harvested, or simply burned, faster than it is replaced. And wood in the form we use for construction has to be cut, dried, chemically treated, and transported, all with some nonrenewable consequences. Similar reservations apply to natural fibers, natural rubber, and animal-derived materials like leather. Few of the materials we use today qualify as truly renewable in substance and in scale.

Mechanical properties. The mechanical properties of a selection of the materials in Fig. 11.2 are plotted in Fig. 11.3. The construction industry uses materials in greater quantities than any other (see cover images of this chapter). Much construction is in less developed countries where steel, concrete, and fired brick are not readily available, forcing the use of materials that occur naturally. Architects with concern for the environment and a love of preindustrial building materials now use an interesting range of near-renewable materials, and these are worth exploring. Bamboo and soft and hard woods, as Fig. 11.3 shows, have particularly attractive mechanical strength and stiffness per unit weight. They have been used for construction since the earliest times and in many countries they still are. Concern for the environment has motivated architects in developed nations to reassess the use of wood. "Engineered" wood—Glulam and other laminates—has properties that are less variable, stimulating its use for domestic architecture and for multilevel buildings with up to 10 stories.

Data sources for wood properties generally list values for clear wood samples, meaning samples with no knots or other defects. These are not, however, the data needed for mechanical design. As explained in the introduction, design handbooks list "allowables"—property values that will be met or exceeded by, say, 99% of all samples (meaning the mean value minus 2.3 standard deviations). Natural

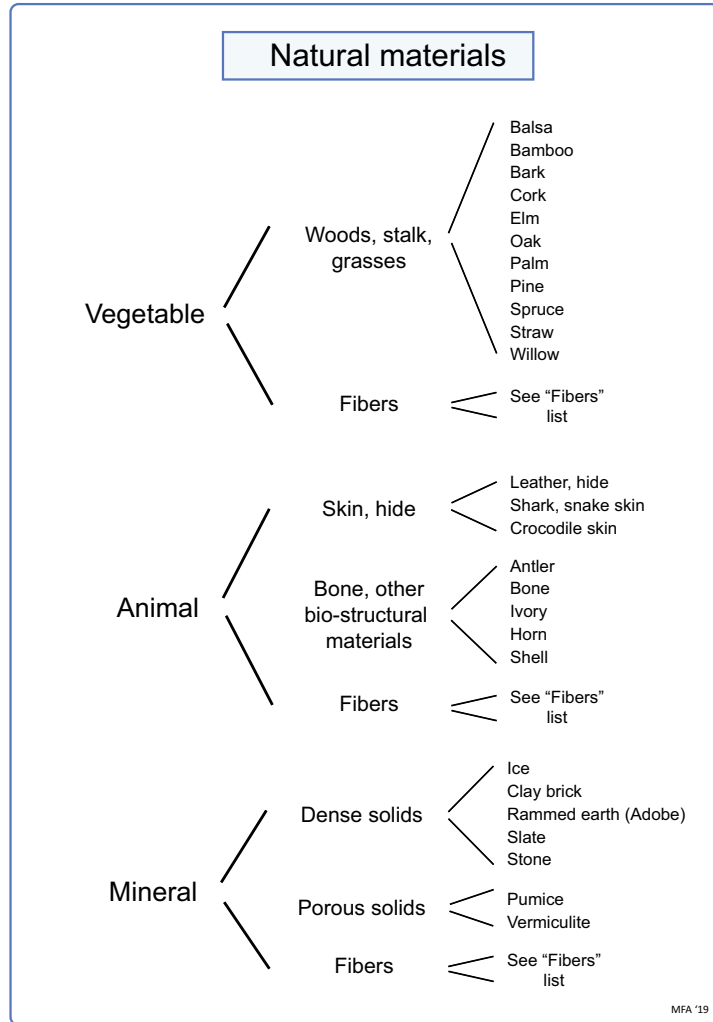


FIGURE 11.2 A hierarchy of natural structural materials (The "Fibers" list appears in Figure 11.8).

materials like wood show greater variability than human-made materials like steel, with the result that the allowable values for mechanical properties may be only 70% of the mean. There is a second problem: large structures made of wood contain knots, shakes, and sloping grain, all of which degrade properties. To deal with this the wood is "stress-graded" by visual inspection or by automated methods, assigning each piece a grading G between 0 and 100, meaning that the properties listed for clear wood are knocked down by the factor $G/100$. Finally, in building construction, there is the usual requirement of sound practice, requiring an overall safety factor, typically 2.25. The result is that the permitted stress for design may be as low as 20% of the values listed as "average" properties.

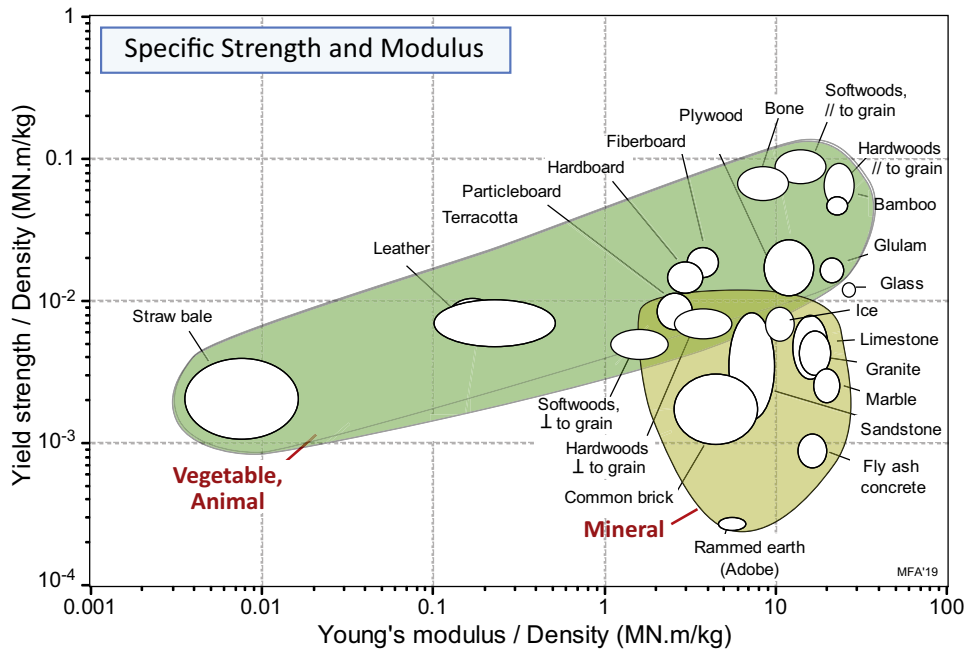


FIGURE 11.3 Specific strength and specific modulus for natural materials.

Newsclip: “High-rise buildings made of wood.”

Seeking to be greener, builders are choosing timber for offices, apartments and campus buildings. Proponents scored a huge win last month when the International Code Council concluded that wooden buildings could climb as high as 18 stories.

The New York Times, January 7, 2019

Engineered wood like Glulam has reduced variability, allowing greater confidence.

Newsclip: “Furniture that destroys forests: crackdown on ‘rampant’ trade in rosewood.”

Governments have launched a crackdown on the rampant billion-dollar trade in rosewood timber that is plundering forests across the planet to feed a booming luxury furniture.

The Guardian, September 29, 2016.

It is difficult to protect the environment when the local economy is deprived of income by so doing.

Thermal properties. Buildings for human habitation must provide shelter and generally have to be heated or cooled, so the choice of construction material is partly conditioned by the local climate. Two thermal properties are important in this choice: the thermal conductivity λ (J/m·K) and the thermal mass per unit volume, ρC_p (J/m³·K), where ρ is the density and C_p the specific heat capacity (Fig. 11.4). The first, λ , controls the loss or gain per unit area through the wall. The second, ρC_p , measures the heat energy absorbed to raise the temperature of unit volume of the wall by 1°C, or rejected when it cools by 1°C. A wall with a high thermal mass is slow to heat up and slow to cool. The time lag for heating or cooling depends on how rapidly heat diffuses into or out of a structure, measured by the thermal diffusivity, a (m²/s):

$$a = \frac{\lambda}{\rho C_p}. \quad (11.1)$$

The thermal lag time t_l (seconds) for heat to diffuse into or out of a wall of thickness w is well approximated by:

$$t_l = \frac{w^2}{2a}. \quad (11.2)$$

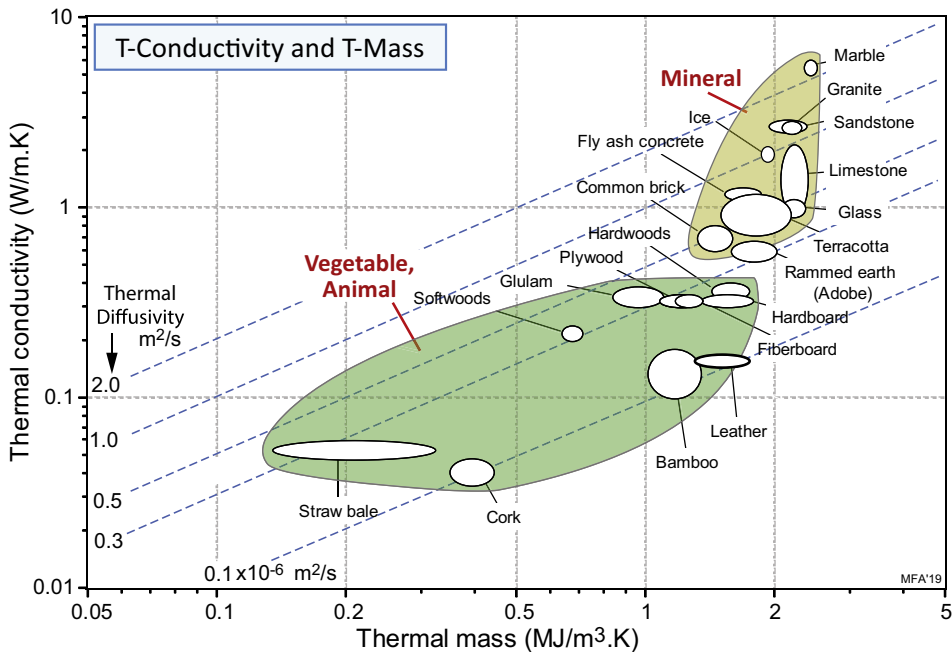


FIGURE 11.4 The thermal conductivity and thermal mass of building materials. The contours show the wall thickness required to give a thermal cycle time of 12 hours.

Example: Thermal mass of renewable building materials. Compare the thermal masses per unit area of walls made of adobe, softwood, and straw bales. The table lists typical wall thickness, density, and specific heat for the three materials.

Answer. The thermal mass per unit area is listed in the last column. Softwood walls, with the lowest thermal mass, require the least energy to heat up. Adobe walls require almost six times more energy.

Material	Wall thickness, w (mm)	Density, ρ (kg/m^3)	Specific heat, C_p (J/kg · K)	Thermal mass/ unit area $\rho C_p w$ (MJ/m ² · K)
Adobe	200	1850	710	0.26
Softwood	50	510	1700	0.04
Straw bale	450	123	1680	0.09

Example: Thermal management with renewable building materials. Compare the thermal lag time t_l for the same three materials and wall thicknesses of the previous example.

Answer. The table lists the thermal properties and the lag times. The softwood wall heats up quickly. The adobe and straw bale walls take much longer.

Material	Wall thickness, w (mm)	Thermal conductivity λ (W/m · K)	Thermal diffusivity $a = \lambda / \rho C_p$ (m ² /s)	Thermal lag time $t_l = w^2 / 2a$ (hours)
Adobe	200	0.57	0.44×10^{-6}	12.6
Softwood	50	0.26	0.3×10^{-6}	1.2
Straw bale	450	0.05	0.25×10^{-6}	11.3

Newsclip: “Council houses made of straw.”

Local authorities (in Britain) are rushing to embrace traditional building materials.

The Sunday Times, July 31, 2011

Several authorities are experimenting with straw bale construction. The bales are stacked into walls and surfaced with lime plaster that allows the straw to breathe. Heating costs are said to be one-third of those of a traditional house of the same size.

11.3 Biopolymers

Commodity plastics are made from fossil hydrocarbons, particularly oil. This is a concern for four reasons:

- oil is a nonrenewable resource;
- fossil hydrocarbons, when combusted, release the carbon they contain into the atmosphere;
- dependence on oil as a feedstock brings the risk of cost volatility; and
- most oil-based polymers degrade only very slowly, creating a long-term problem of “polymer pollution.”

Biopolymers,¹ in contrast, are plastics made from biomass (Fig. 11.5). Hydrocarbons made by fermentation of biomass (corn, soya, sugarcane) can be polymerized to make bio-polyethylene (PE) and bio-polypropylene (PP). These so-called “drop-in” biopolymers have properties that are identical to those of their oil-based equivalents, which they directly replace. Other biopolymers, such as polylactide (PLA) and polyhydroxyalkanoate (PHA), are uniquely biological in origin and require their own processing methods because of the narrow window between the processing temperature and the decomposition point.²

Mechanical properties. If biopolymers are to compete successfully with oil-based plastics, they must have comparable properties and price. How do they compare? Fig. 11.6 shows two important property groups: the specific stiffness E/ρ and specific strength σ_y/ρ , where E is Young’s modulus, σ_y is the yield strength, and ρ is the density. It shows that bio-plastics have mechanical properties that are broadly comparable to those of conventional polyethylene terephthalate (PET) or PP.

Environment: carbon footprint and land area. Bio-plastics are widely perceived to have a better eco-character than oil-derived polymers, but evidence does not entirely bear this out. Fig. 11.7 shows the carbon footprint of bio- and oil-based plastics: thermoplastic starch (TPS) and PHA have significantly lower footprints than PP and PE, but the others do not. At first sight it seems surprising that a plastic based on natural materials is nearly as carbon intensive as one made from oil. It is because the fermentation or processing needed to make bio-resins requires heat and thus carries an energy and carbon burden, and the subsequent polymerization step for bio- and oil-based plastics makes almost identical contributions to both.

The land area required to synthesize conventional oil-based polymers is small. That for bio-plastics is large. At present the predominant feedstock for bio-plastic

¹Biopolymers are used for packaging (NatureWorks PLA), disposable cutlery and containers (Cereplast’s PLA blend, Novamont’s Mater-Bi starch resin), dental care items and medical items (Cereplast), and agricultural turf stakes (Telles PHA).

²<http://www.ptonline.com/articles/injection-molding-bio-plastics-how-to-process-renewable-resins>.

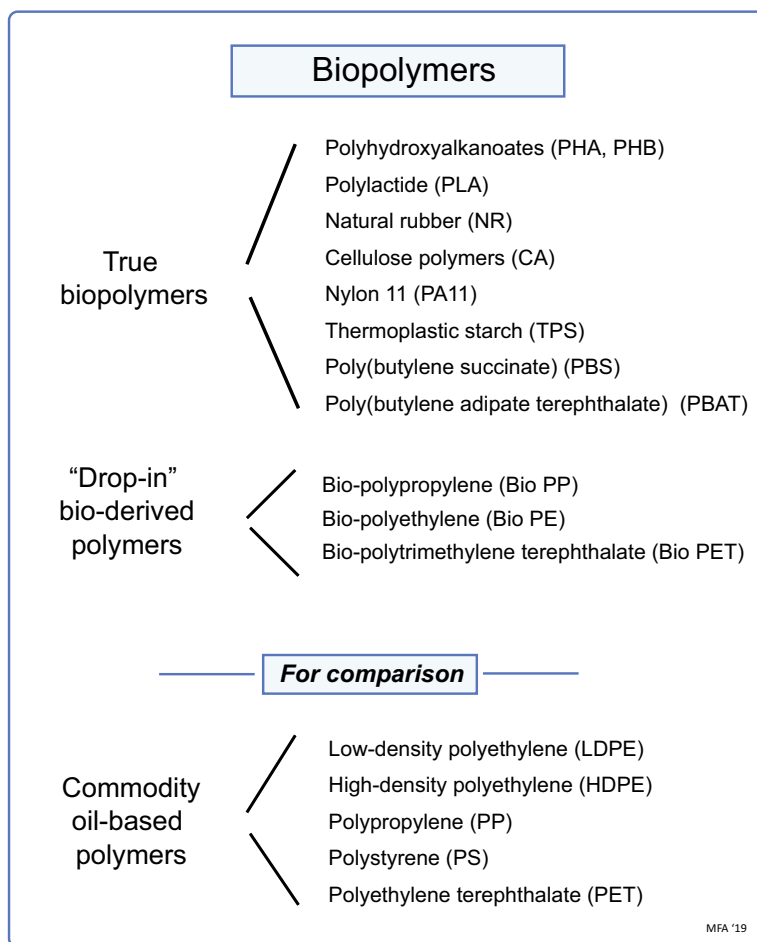


FIGURE 11.5 *Biopolymers and the commodity oil-based polymers with which they compete. PLA, PHA, TPS, and blends of these with PE, PP, and PET are bio-degradable; bio-PP and bio-PE are not.*

production is corn. It takes 3 m² of fertile land to make 1 kg of PLA per year. At that level the production of 12 million tonnes of PLA per year requires 36,000 km² of fertile land. For comparison, the land area of the Netherlands is 41,500 km² but only a part, 23,000 km², is designated as agricultural land.

Economics. Commodity plastics (PP, PE, poly(vinyl chloride), PET, polystyrene, acrylonitrile butadiene styrene) all have prices between \$1.5 and \$2.6 per kilogram. Bio-plastics today cost more than that (Fig. 11.7). In a straight substitution of a bio-plastic for a conventional polymer, it is the price per unit volume rather than per unit weight that is significant, but since all these plastics have almost the same density, the conclusion is the same.

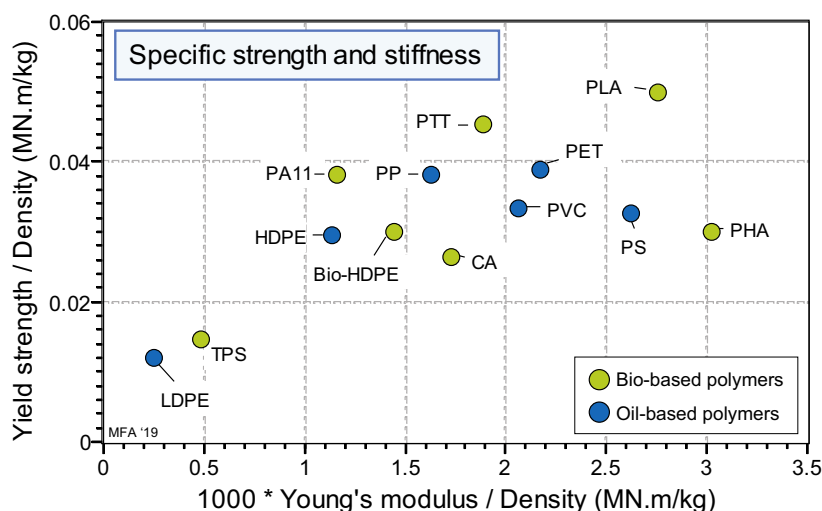


FIGURE 11.6 The mechanical properties of oil and bio-based plastics.

And polymer pollution? Some bio-plastics biodegrade in the true sense of returning their constituents to the biosphere in the form from which they were first drawn. But not all. More than half the present-day production is “drop-in” bio-plastics (those identical in chemistry with their oil-based equivalent), such as bio-PE, and these, of course, do not biodegrade.

11.4 Fibers, natural and synthetic

From the earliest recorded times, humans have used natural fibers to meet basic needs of shelter, clothing, ropes, and nets. Vegetable fibers are derived from stalk (jute, hemp, ramie), stem (banana, palm, bamboo), leaf (palm, sisal, agave), husk

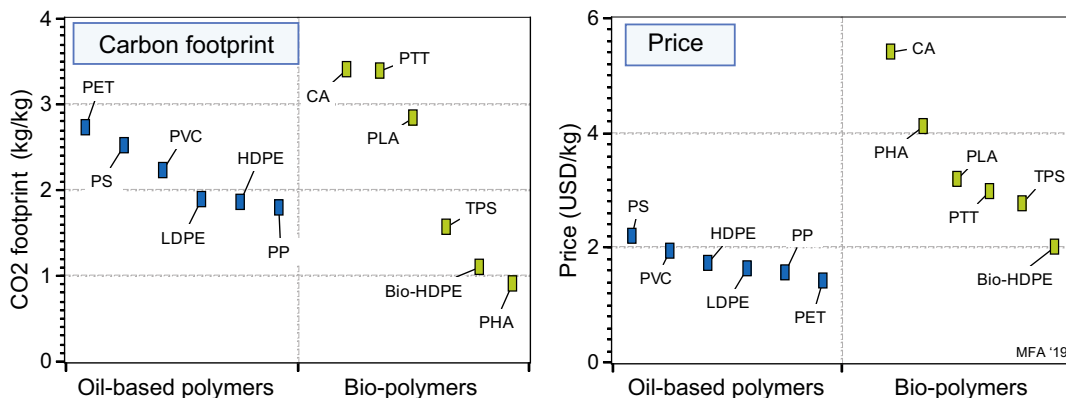


FIGURE 11.7 The carbon footprint and price of oil and bio-based plastics.

(coir), and seeds (cotton); protein fibers from hair, fur, wool, insect cocoons, and webs (Fig. 11.8). From them come a remarkable range of fabrics: linen (flax), calico (cotton), gabardine (wool), brocade (silk), and many more.³

Since the beginning of the 20th century, many natural fibers have been replaced by those that are synthesized, mainly from oil. The production of synthetic fibers first exceeded that of those of nature only recently (2002). Today synthetics account for almost 70% of the fiber market and 20% of all polymer production. Why?

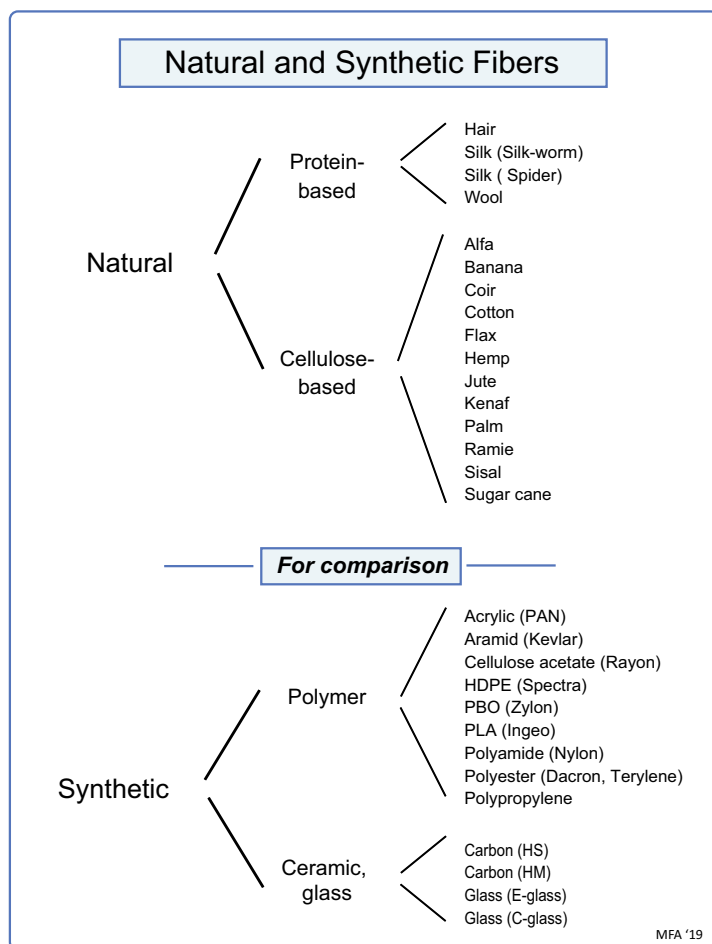


FIGURE 11.8 Natural and synthetic fibers.

³<http://www.textileschool.com/articles/356/history-of-fibres-natural-and-manmade-fibres>

- Cost: PP and polyester (PET) fibers are cheaper than cotton and flax and are more reproducible.
- Performance: The recently developed “super-fibers,” Kevlar, Spectra, Dyneema, Vectran, and Zylon, have properties that, per unit weight, outperform any natural fiber.

Four synthetic fiber types dominate the market: acrylic, nylon, polyester, and polyolefin.⁴ Between them they account for 98% of synthetic polymer production.

Today, fibers are used in almost every industrial sector and—as Fig. 11.9 demonstrates—they are used in enormous quantities. Some are very cheap, costing less than \$1/kg. Others, particularly the newer super-fibers, are much more expensive, costing up to \$100/kg. The product of price and annual world production gives an approximate measure of the global market size; it is shown as diagonal contours on the figure. That for the three most-used natural fibers—cotton, jute, and wool—is large, as is that for the four most-used synthetics—polyester, PP, nylon, and celulosics. By contrast, the global market size for the super-fibers remains small.

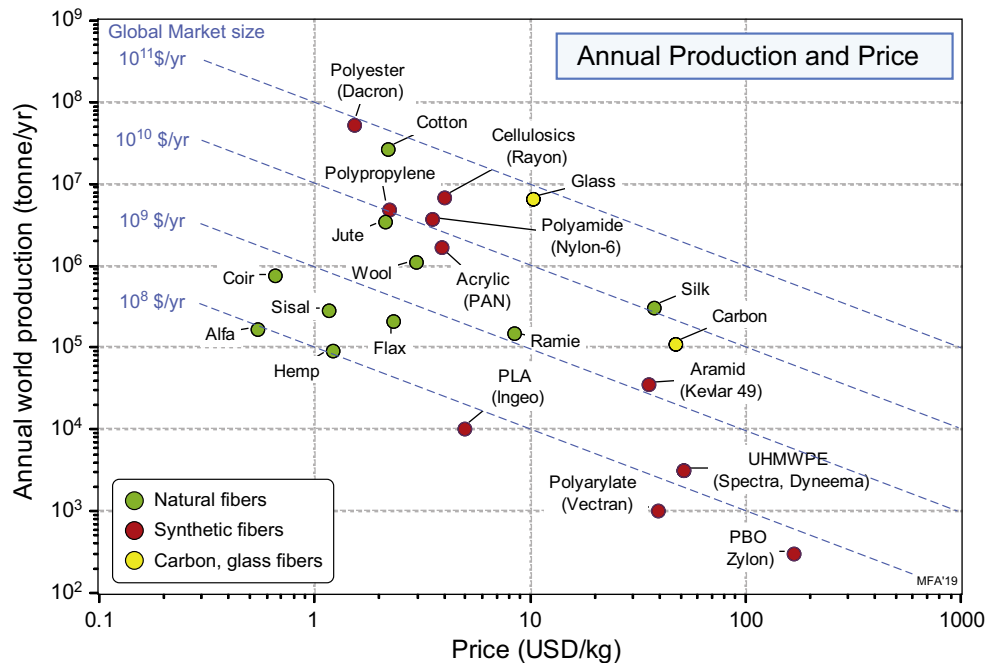


FIGURE 11.9 Approximate price and global production of fibers, with contours of global market value.

⁴<https://www.syntheticgrasswarehouse.com/history-synthetic-fibers/>.

Mechanical properties. Fig. 11.10 compares the specific tensile strength, σ_t/ρ , of natural fibers (green) with synthetic polymer fibers (red) and carbon and glass (yellow). Super-fibers lie at the upper left, outperforming all natural fibers.

The energy required to strain a fiber to its breaking point (the “work capacity”) is:

$$U \approx \frac{1}{2} \frac{\sigma_t \epsilon}{\rho},$$

and it is important in spinning and weaving when fibers are exposed to tension. It is shown in Fig. 11.11. The striking feature of the figure is the enormous work capacity of both viscid and drag-line spider silk, despite the fact that neither is particularly strong.

Environmental properties. One might expect that the carbon footprint of natural fibers would be lower than that of the oil-based synthetics. Fig. 11.12 shows that this is indeed the case, and that the carbon emissions associated with the super-fibers is particularly high. What is not shown is the associated water consumption, the data for which are imprecise; all indications are that natural fibers and semisynthetics (PLA, cellulotics) demand more water than the pure synthetics.

11.5 Bio-based composites

Bio-composites. There was a time when cars, like carriages, were largely made of natural materials: wood, fabric, natural rubber; only the engine and the drivetrain were metal. By the 1970s human-made materials had replaced them all. Today, however,

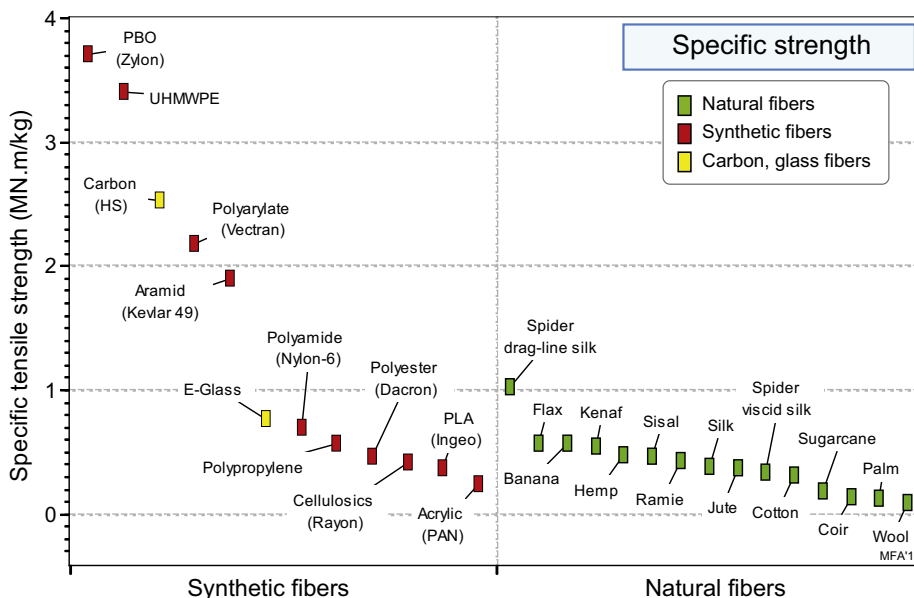


FIGURE 11.10 Specific strength of fibers.

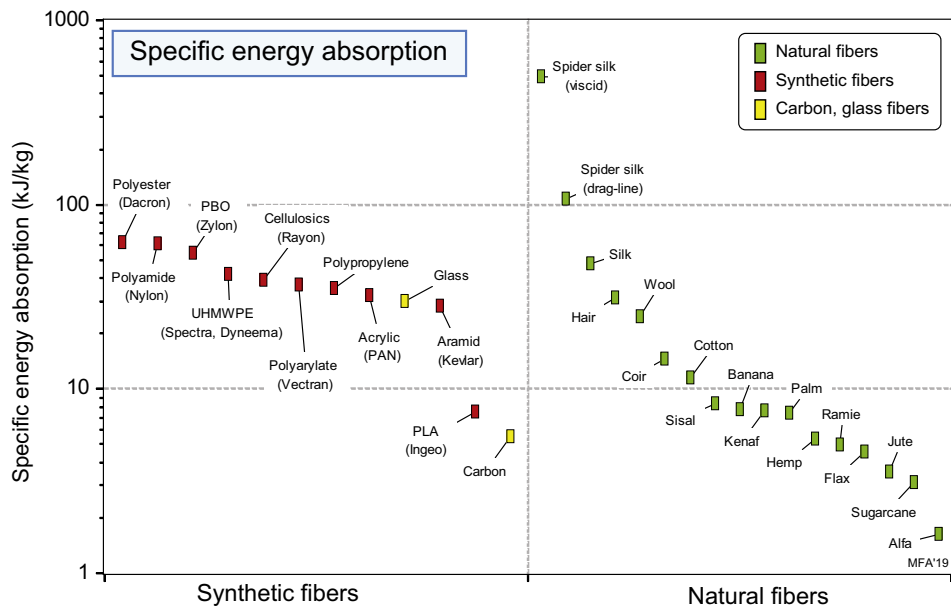


FIGURE 11.11 Approximate energy absorption in fibers.

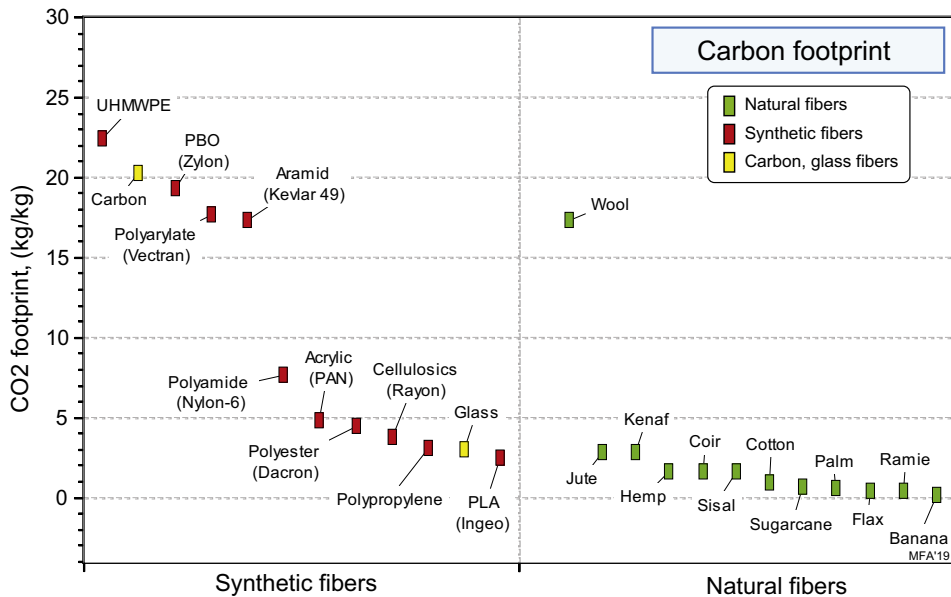


FIGURE 11.12 Approximate carbon footprint of fibers in kg/kg.

natural materials are regaining ground, driven by the environmental agenda. Thus far their application has been limited to trim (flax-fiber-reinforced epoxy or furan for interior door panels), sound insulation (recycled cotton fibers), and seat cushions (coconut fibers in latex), but interest in using plant fibers as reinforcement is growing.⁵ The fibers of most interest—flax, sisal, jute, hemp, kenaf, and coir—are annual crops that grow quickly. Most current bio-based composites use these as reinforcement in thermosetting phenolic or epoxy resins, but these can't be recycled. Attention has now shifted to plant-fiber-reinforced thermoplastics, particularly PP, produced in sheet form that can be compression molded to shape (Fig. 11.13). The obstacles that remain are the cost, the variability of fiber quality, and the limit on the processing temperature (<220°C) required to avoid fiber damage.

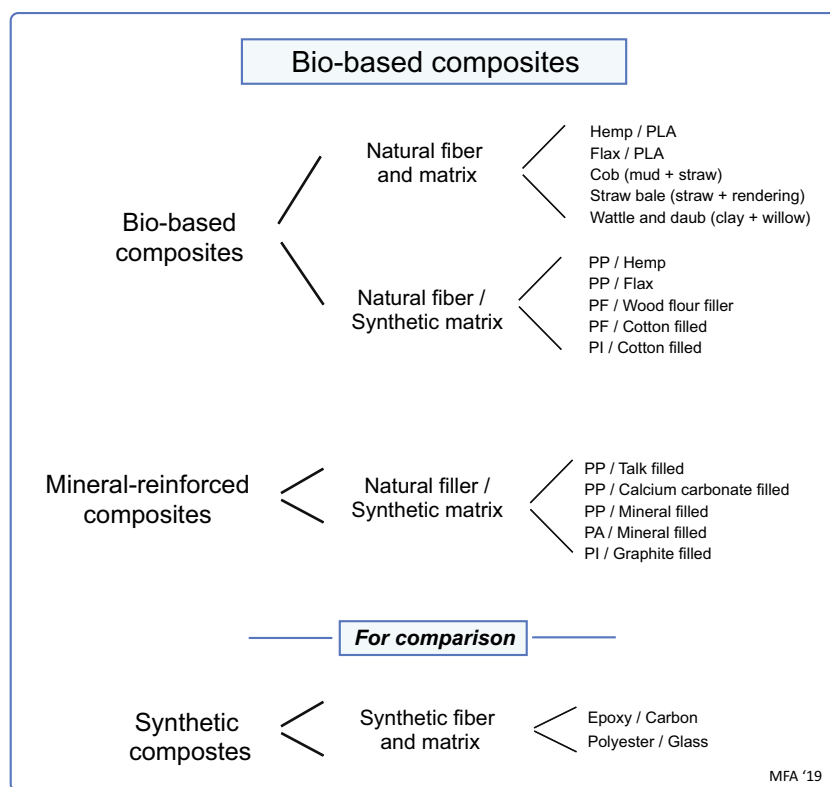


FIGURE 11.13 *Bio-based polymers and composites.*

⁵Using natural fibers as reinforcement for composites is not a new idea: Henry Ford developed Fordite, a composite of wheat straw, rubber, sulfur, and silica, in the 1920s. It ended up in steering wheels.

Recent reviews⁶ assemble data for bio-based composites and for the fibers and matrix materials on which they are based. These data,⁷ together with estimates for carbon footprint and price, are presented in the charts that follow.

Mechanical properties. Composites have attractive mechanical properties per unit weight. Figs. 11.14 and 11.15 give overviews of specific stiffness and specific strength for synthetic and bio-based composites. The two charts have identical scales. The bio-based composites occupy a space that overlaps that occupied by glass-fiber-reinforced composites. No bio-based composites can compete with those reinforced by carbon.

Eco-properties and price. Fig. 11.16 compares the CO₂ footprint of synthetic and bio-based composites. With some exceptions, bio-based composites have a lower footprint than synthetic composites. Fig. 11.17 plots price. Bio-based composites cost about the same, per kilogram, as those reinforced with glass.

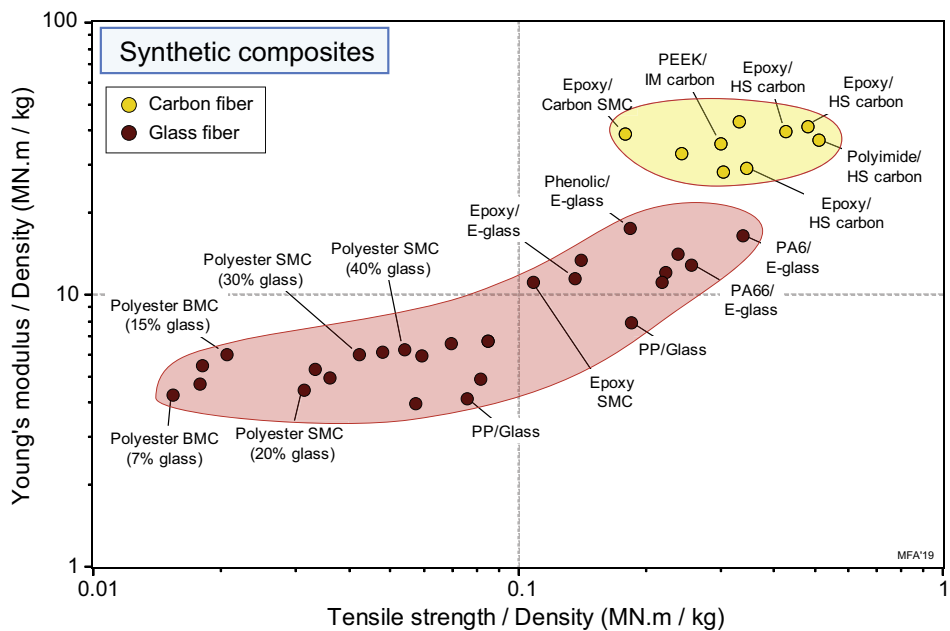


FIGURE 11.14 Synthetic polymer–matrix composites already in the database.

⁶Shah (2013, 2014), Dicker et al. (2014), Pickering et al. (2016).

⁷Brechbühl and Ashby (2018).

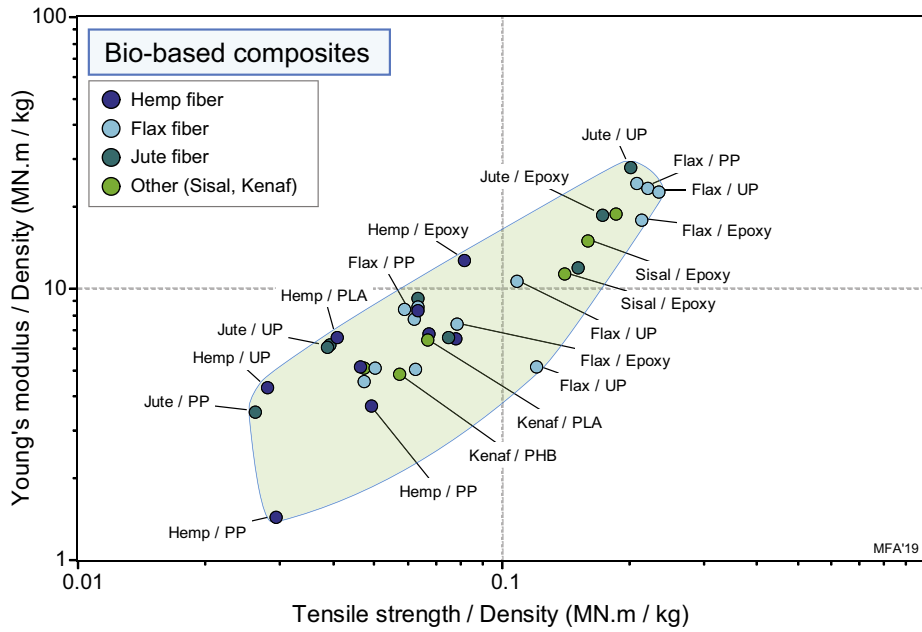


FIGURE 11.15 *Bio-based composites.*

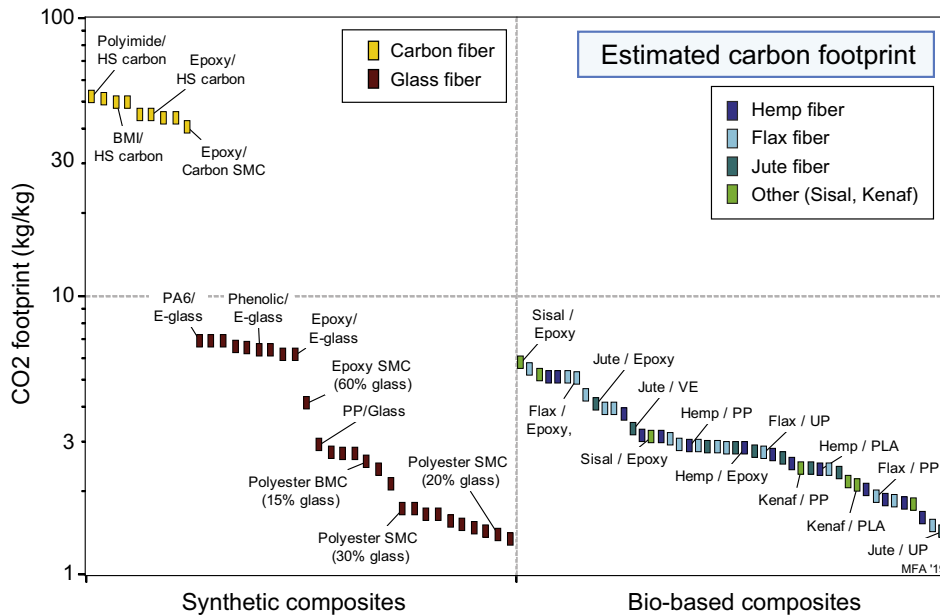


FIGURE 11.16 *Estimated carbon footprint of synthetic and bio-based composites.*

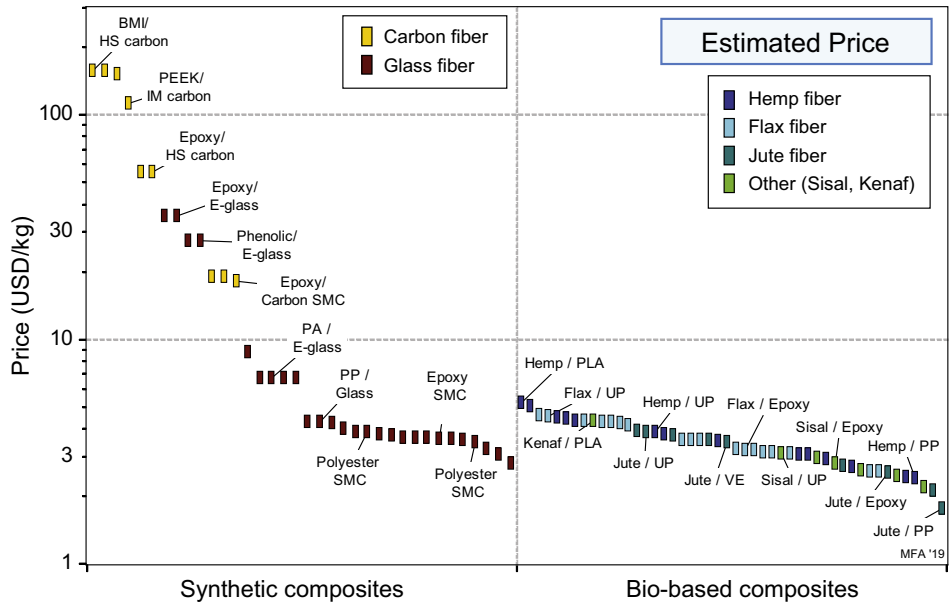


FIGURE 11.17 Estimated price of synthetic and bio-based composites.

Newsclip: “Motive unveils the kestrel interior featuring advanced bio-composites.”

The Motive Kestrel, a 3 door, 4 passenger, electric vehicle, will be made using (hemp fiber) bio-composite material in its body as well as in the interior.

NetComposites, July 19, 2019

Hemp has a long history with automakers, dating from 1941 when Henry Ford unveiled a car body made primarily out of organic fibers, hemp included.

11.6 Summary and conclusions

For millennia, human society has drawn on natural materials to fill most of its needs for shelter, clothing, tools, and self-preservation. Starting around 5000 years ago, small quantities of lead, bronze, and then iron replaced natural materials in a few of these functions, but it was not until the 20th century that natural materials were comprehensively sidelined, first by steel and then, about midcentury, by plastics. The final triumph of synthetics was polyester’s displacement of cotton as the most-used fiber in 2002.

Historically, natural materials were sourced locally. Their displacement by synthetics has created the need for global supply chains to give resource-poor nations access to the ores and feedstock needed to make them. The resulting consumption of energy and resources, the environmental consequences of ever-expanding industrialization, and the strategic and geopolitical challenges of supply-chain management (Chapter 12) have stimulated a reassessment. Can bio-based materials, with their gentler eco-touch and renewability potential, play a larger role in the economy of the 21st century?

Biopolymers—particularly those based on cellulose (cellulose acetate), starch (TPS), or lactic acid (PLA)—have an established and growing market. Obstacles to wider expansion are:

- The price: Biopolymers and bio-composites with competitive property profiles are not cheap.
- The variability: The properties of bio-materials depend on geography and fluctuations of weather.
- More challenging molding and extrusion conditions must be met to avoid decomposition.

There are probably ways of dealing with all of these, but they are not the ultimate difficulty. That is on a different scale. The world has now consumed itself into a corner: there is not enough productive land to both grow the food we need and provide feedstock for bio-materials or bio-fuels on a really large scale. Alternatives using oceanic plant life or freshwater algae are under study, but not yet demonstrated as viable.

Of all the forms into which materials can grow or be made, that of a fiber is perhaps the most intimate. Almost all clothing is woven from fiber. The paper on which this book is printed is compacted fiber. The carpet on which my feet rest as I type this page is fiber. I wash with a facecloth and dry my face with a towel—all fiber. Even the hair that keeps my head warm (though I haven't got much now) is fiber. Until surprisingly recently (2002), natural fibers dominated the textile market. Since then, synthetics have displaced them. Reverting to a greater use of cotton, flax, or wool is attractive to many, but the demand for arable land to cultivate them again comes head to head with food production.

Bio-based composites are established and their use is growing. The properties shown in this chapter demonstrate that they can compete in mass and cost with metals and synthetic composites in nondemanding applications. And they bring the eco-satisfaction of renewable content, low carbon footprint, and—for some—the potential for recycling.

But would you want to ride a bicycle with flax-fiber-reinforced PLA forks? Before you did, you might wish to know about its other characteristics. Fatigue strength? Fracture toughness? Durability? Little data exist for these. There is a clear need for standards, test data, and a better understanding of design allowables for bio-based polymers and composites. Their use in safety-critical components must wait until fuller characterization is available.

11.7 Further reading

Data sources for natural materials

- Beukers, A. and van Hinte, E. (1998) "Lightness. The inevitable renaissance of minimum energy structures", Rotterdam: 010 Publishers.
- Currey, J.D., Wainwright, S.A., and Biggs, W.D. (1982) "Mechanical design in organisms", Princeton University Press, Princeton, NJ.
- Maniatidis, V. and Walker, P. (2003), "A review of rammed earth construction", Natural Building Technology Group, Department of Architecture & Civil Engineering, University of Bath, Bath, UK. <http://people.bath.ac.uk/abspw/rammedearth/review.pdf>. (*A comprehensive review of rammed earth properties and construction.*)
- PROSPECT (Version 2.1), Oxford Forestry Institute, Department of Plant Sciences, Oxford University, South Parks Road, Oxford OX1 3RB, UK (1995). The full database can be down-loaded from www.plants.ox.ac.uk/ofi/prospect/index.htm. (*A database of woods, with illustrations of structure, information about uses, origins, habitat, and more.*)
- Vincent, J.F.V. (1990) "Structural biomaterials" (revised edition), Princeton University Press, Princeton, NJ.
- Vincent, J.F.V. and Currey, J.D. (1980) "The mechanical properties of biological materials" (Proceedings of the symposia of the society for experimental biology; no.34), Cambridge: Cambridge University Press for the Society for Experimental Biology.
- Wegst, U.G.K. and Ashby, M.F. (2004) "The mechanical efficiency of natural materials". *Philosophical Magazine A* 84, 2167–2181.
- Woolley, T. (2006) "Natural building – A guide to materials and techniques", The Crowood Press Limited, Ramsbury, UK. (*A well-illustrated introduction to traditional building materials and their present day modifications.*)

Data sources for biopolymers

- Furan (2010) www.biocomp.eu.com/uploads/04_THERMOSET_BIOPOLYMER_MATERIALS-TFC.pdf. (*Background on the furic acid–based bio-polymer, furan.*)
- van Beilen, J.B. and Poirier, Y. (2007) "Prospects for biopolymer production in plants". *Adv Biochem Engin/Biotechnol* vol. 107. pp. 133–151.
- Wool, R.P. and Sun, X.S. (2005) "Bio-based polymers and composites", Elsevier, Amsterdam, Netherlands. (*A text introducing the chemistry and production of bio-polymers.*)

Data sources for fibers

- Ashby, M. (2018) "Fibers in the CES EduPack – a White Paper", Granta Design, Cambridge, [www.Grantadesign.com/education](http://www.grantadesign.com/education).
- Carmichael, A. (2014) "Man-made fibers continue to grow" Textile World", <https://www.textileworld.com/textile-world/fiber-world/2015/02/man-made-fibers-continue-to-grow/>.
- Cordage Institute (2018) "Fibers for Cable, Cordage, Rope and Twine", Cordage Institute Comparative Reference, <http://www.ropecord.com/cordage/publications/docs/CI2003.pdf>.
- Cyr, Annie (2016) "The guide to textile fibers: clothing and fashion industry", 2nd edition, CreateSpace Independent Publishing Platform. <https://www.guide-textilefibers.com>.
- Hearle, J.W.S. (2001) "High performance fibres", The Textile Institute, CRC and Woodhead Publishing Ltd, UK.
- Menghe, M and Xin, J. (Editors) (2017) "Engineering of high-performance textiles", Woodhead Publishing.
- Thompson, R. and Thompson, M. (2014) "Manufacturing processes for textile and fashion design professionals", Thames and Hudson Ltd. <http://www.rieter.com/en/rikipedia/articles/rotor-spinning/applications-engineering/fiber-properties/fiber-tenacity-and-fiber-elongation/>.

Data sources for bio-composites

- Baillie, C. (Editor), (2004) "Green composites", Woodhead Publishing Ltd, London UK. (*A collection of papers dealing with natural fibers and composites based on them.*)
- Brechbuhl, E. and Ashby, M.F. (2018) "The CES Bio-composites Database – a White Paper", Granta Design Limited, www.grantadesign.com/education.
- Dicker, M.P.M., Duckworth, P.F., Baker, A.B., Francois, G., Hazzard, M.K., and Weaver, P.M. (2014), "Green composites: A review of material attributes and complementary applications", Composites Part A Vol. 56, pp. 280–289.
- Pickering, K.L., Auran Efendy, M.G., and Le, T.M. (2016) "A review of recent developments in natural fibre composites and their mechanical performance", Composites Part A Vol. 83, pp. 98–112.
- Shah, D.U. (2013) "Developing plant fibre composites for structural applications", Journal of Materials Science Vol. 48, pp. 6083–6107.
- Shah, D.U. (2014) "Natural fibre composites: comprehensive", Materials and Design Vol. 62, pp. 21–31.
- Wool, R.P. and Sun, X.S. (2005) "Bio-based polymers and composites", Elsevier, Amsterdam, Netherlands. (*A text introducing the chemistry and production of bio-polymers.*)

11.8 Appendix: Natural materials—brief portraits

Mineral-based materials. Ice. When the temperature drops below 0°C , fresh water freezes; seawater does so at -4.2°C . Ice is easy to cut into blocks and stack into walls, arches, and domes; it is a practice thousands of years old. Today ice hotels lure winter tourists to Norway, Finland, and Sweden. While the temperature remains below zero, the structure is permanent. When it rises above zero, the entire structure reverts to pure water, ready to be frozen again. It is hard to think of a material more renewable than that.

Stone and lime. Stone may not be renewable, but one might think the resource from which it is drawn is nearly infinite. True in general, but not in particular: Carrara marble, Sydney sandstone, Portland stone, Welsh slate—all are now scarce, the most accessible deposits already exploited. More generally, stone is an eco-friendly material, durable and reliable. “Dressed” stone—the material of city banks, venerable universities, and corporate head offices—is expensive: dressing doesn’t come cheap. Field stone, by contrast, is there to be picked up. “Dry stone” walls are made by skilled stacking of stones as found. They work well as field boundaries but they are not load-bearing. Stone bonded with a lime mortar, however, is robust and durable. Roman arenas, amphitheaters, and aqueducts built with this combination still stand today.

Rammed earth and adobe. Soil is available almost everywhere. Mix it with straw or hair and a little lime cement, stomp it down between wooden shuttering, let it set, and you have a wall that will support a light roof. If the earth wall is thick enough, its thermal mass keeps the interior cool when it’s hot outside and warm when it’s cold.⁸ Adobe is the traditional building material of Mexico and parts of Africa and is still widely used today.

Brick, fired and unfired. Ordinary bricks are fired at between 800°C and 1200°C . Clay bricks made from compressed clay-rich earth are not fired, so their embodied energy is low. Their compressive strength, too, is low (of the order 0.1 MPa) so they are used for non-load-bearing walls or infill for timber frame constructions. Unfired bricks have a high density ($1500/\text{m}^3$), giving them good sound-damping properties, a high thermal mass, and a low thermal conductivity, making buildings with thick brick walls cool in summer, warm in winter.

Mineral fibers: asbestos. Asbestos is a hydrated form of magnesium silicate with a sheet-silicate structure that rolls up to form hollow tubes about $4\text{ }\mu\text{m}$ in diameter and a few millimeters long. It is used to reinforce cement to give flat sheets, tiles, pipes, and guttering and as reinforcement in phenolic resin for brake and clutch lining. Its use is now restricted because some grades are carcinogenic.

Mineral foams: pumice and vermiculite. Vermiculite is a lamellar form of hydrated magnesium–aluminum–iron–silicate that resembles mica. It is used in its exfoliated (expanded) form, made by heating at 1000°C , reducing its density from

⁸Typical rammed earth walls have a density of $1950\text{ kg}/\text{m}^3$, a compressive strength of 0.6 MPa , a thermal mass of $1.8\text{ MJ}/\text{m}^3\cdot\text{K}$, and a thermal conductivity of $0.6\text{ W}/\text{m}\cdot\text{K}$ (Maniatidis and Walker, 2003).

2300 kg/m³ to about 100 kg/m³. It is used for nonflammable thermal insulation, fire protection, and sound absorption.

Vegetable-derived materials (except fibers)

Tree wood. All tree woods have broadly the same chemical composition: about 50% wt% crystalline cellulose fibers in a matrix of hemicellulose and lignin with a few percent oily extractives that give the wood its color and smell. The great range of properties exhibited by different woods is largely due to the difference in fiber structure and relative density (the fraction of solid in the wood), which ranges from 0.1 to 0.85, giving the woods a density between 140 and 1050 kg/m³.

Palms are monocots, more closely related to grasses and ferns than to trees. Some palms grow to a considerable height, supporting it by increasing the thickness and amount of lignin in the older cell walls, giving the stems a gradient structure, thickest at the outside.

Bamboos are grasses. The hollow, cylindrical stem derives its strength and stiffness from its tubelike shape, reinforced by parallel fiber bundles that occupy about 50% of the cross section. Like palms, bamboos do not thicken by secondary growth and show no growth rings.

Cork. All trees have a thin layer of cork just below the bark. The cork oak, *Quercus suber*, is unique in that, at maturity, the cork forms a layer 10–30 mm thick around the trunk. Structurally, it is a low-density, polymeric closed-cell foam. Cork contains suberin, a fatty acid, and waxes that make it impervious to air, water, and alcohol (think wine bottles). Its function in nature is to protect the tree from fire and from water loss, and perhaps to discourage damage by animals (cork is pretty indigestible stuff).

Straw and reed. Straw, a by-product of agriculture, has long been used for roofs and wall insulation. Straw bales are like building blocks: stack them up and you create a wall. Surface them with earth plaster or wood and they become durable. The walls have low thermal conductivity and low thermal mass (quite different from rammed earth), so they insulate well. Thatch is a reed, a plant that grows with its base in water, so it has evolved to resist it. Like straw, it insulates and is surprisingly durable: a well-thatched roof lasts for 80 years.

Animal-derived materials (except fibers)

Bone, tooth, and shell. Bone is a composite of hydroxyapatite (hydrated calcium phosphate) and collagen. It provided early humans with tools and ornaments. Today it is calcined for bone china. Tooth, too, is hydroxyapatite in a dense form, familiar as ivory. Shell is calcium carbonate in the form of calcite or aragonite. Where it is plentiful it is calcined to make lime for cement or crushed as a filler in concrete.

Hide and skin. Real leather has become a symbol of luxury, the material of fashion boutiques, expensive furniture stores, and high-end automobiles. Snake-skin bags and crocodile-skin shoes exist but meet with disapproval in some

quarters. Most uses of hide and skin are now capably met by polymers such as poly(vinyl chloride) and polyurethane.

Fibers: Natural vegetable fibers

Coir (from Malayalam “kayar,” cord), a coarse fiber extracted from the hairy outer shell of a coconut, is used in mats, rope, brushes, and sacking. The coir fiber is relatively waterproof and is one of the few natural fibers resistant to damage by salt water.

Cotton is the fiber from the blossom of the plant *Gossypium*. There are many species, all chemically identical (95% cellulose with a little wax) but differing in fiber length and slenderness. Cotton is used to make a great range of different fabrics with wonderful names, many deriving from their common use or from the country or town of their origin: voile, calico, gingham, muslin, crepe, damask, cambric, organdie, crinoline, twill, sailcloth, canvas. They differ in the quality of the fiber and the nature of the weave.

Flax is a fiber from the stalk of the linseed plant, *Linum usitatissimum*. As with hemp, the fibers are freed from the stalk by retting, an exceptionally smelly process. Flax is used to make linen and rope, valued for their strength and durability. Flax has been used as a reinforcement for polymer matrix composites.

Hemp comes from the weed *Cannabis sativa*. The hemp fibers, like those of flax, are freed from the stalk by a retting process (for “retting” read “rotting”). The properties of hemp resemble those of cotton. It is used for rope and coarse fabric, and is a potential reinforcement for natural-fiber-reinforced composites.

Jute is a long, soft, shiny vegetable fiber made from the stems of plants in the genus *Corchorus*, family Malvaceae. It is one of the cheapest of natural fibers and is second only to cotton in amount produced and variety of uses. It is spun into coarse, strong threads and woven to make sackcloth, hessian, or burlap. There is interest in using jute as a reinforcement in composites, replacing glass.

Kenaf (*Hibiscus cannabinus*) is a fast-growing stem fiber used to make industrial textiles, ropes, and twines. Emerging uses of kenaf fiber include engineered wood, insulation, clothing-grade cloth, and as a reinforcement in polymer-matrix composites.

Palmyra palm (*Borassus*) is a genus of fan palms, native to tropical regions of Africa, Asia, and New Guinea. Palm fiber (sometimes called “vegetable horsehair”) comes from its leaves. The fibers are springy and strong, making good stuffing for furniture and mattresses.

Ramie (*Boehmeria nivea*), from the stem of a flowering plant in the nettle family, is one of the strongest natural fibers. It is used for cordage and thread and is woven into fabrics for household furnishings (upholstery, canvas) and clothing, frequently in blends with other textile fibers.

Sisal fiber is derived from an agave, *Agave sisalana*. It is valued for cordage because of its strength and durability. Like coir, it is resistant to deterioration in saltwater. The higher-grade fiber is converted into yarns for the carpet industry. Sisal is now used as a reinforcement in polymer-matrix composites.

Animal-derived fibers

From an energy point of view, animal life is high maintenance. That means that materials derived from animals have a larger embodied energy than those of the vegetable world.

Wools are keratin, the hair or fleece of the sheep, alpaca, rabbit (angora), camel (camel hair), certain goats (mohair, Kashmir), and llamas (vicuna). It is hard wearing (as in wool carpets) and an excellent thermal insulator (as in wool sweaters and blankets). Wool is woven in many different ways to give cloth, tweed, plaid, flannel, or worsted. Wool fabrics are dirt resistant, flame resistant, and, in many weaves, resistant to wear and tearing. But keratin is a protein, easily digested by the larvae of moths if steps are not taken to stop them.

Silks, too, are proteins, the fibers spun by the silkworm to wrap and insulate its cocoon and the spider to trap its prey. Silk is remarkable for its strength and extendability. The combination imparts energy-absorbing qualities that make spiders webs so effective. It is the material of high-altitude balloons, parachutes, and the clothing of film stars and empresses.

Bio-based composites

Cob, wattle and daub. Cob (mud and straw) and wattle and daub (mud mixed with clay over a slender wood lattice) are among the oldest of building materials. Both have high thermal mass and thermal lag, smoothing day-to-night temperature variations. Even today, about half the world's population lives in earth-walled houses.

Straw-bale construction. Straw has been used as a building material for centuries. Today, straw is used both for the structure and as wall infill. Typically, the straw is molded into bales and cut to dimension before being stacked to form thick insulating walls that are either self-supporting or reinforced with a wood frame. The bale walls are plastered or stuccoed on both the interior and the exterior.

Bonded board and linoleum. Plywood, chip board, particle board, and cork board are reconstituted wood, bonded with synthetic adhesive. They can be made from low-quality wood and wood trimmings that would otherwise be burned, making them genuinely green, though not totally carbon free. The appealingly named *meadow board* (made from ryegrass stems that remain after seed harvest), *sunflower seed board* (compacted sunflower hulls), *wheat board* (what's left when the grain has been removed from wheat by threshing), and *peanut husk board* (what it says) are substitutes for wood. These are new developments compared with *linoleum*, invented in 1855 and 100% natural in its ingredients: linseed oil filled with sawdust or cork dust.

Hempcrete. The use of a mix of industrial hemp and lime ("hempcrete") for infill in a wood-frame building is growing. The hemp content of hempcrete—75% by volume—is truly sustainable, grown as fast as it is used and requiring no fertilizer. Hempcrete sequesters 0.3 kg of carbon per kilogram—up to 20 tonnes of carbon in a typical house—giving an eco-credit provided the building lasts long enough.

11.9 Exercises

E11.1. Which classes of natural materials have the highest specific stiffness E/ρ and specific strength σ_y/ρ ? Use Fig. 11.3 of the text to find out.

E11.2. What, approximately, are the thermal conductivity, thermal mass, and thermal diffusivity of sandstone? Read the values as nearly as possible from Fig. 11.4 of the text.

E11.3. A supermarket chain displays delicate fruit in transparent PET packaging that is non-biodegradable. Its customer relations advisor suggests replacing the PET with PLA, a maize-based bio-plastic, of the same thickness. The packaging material must meet a specified stiffness to protect the fruit during delivery. The grade of PET currently used has a modulus of 2.9 GPa with a standard deviation of 0.1 GPa. One supplier of PLA offers sheet with a modulus of 3.1 GPa and a standard deviation of 0.2 GPa, the variability arising from seasonal changes in the maize supply. If the target package stiffness must be met with 95% certainty, is PLA a safer choice than PET? Assume a normal distribution of strength.

E11.4. A batch of polyester fibers has a mean strength of 500 MPa with a standard deviation of 25 MPa. A batch of flax fibers has the same mean strength but a standard deviation of 100 MPa. What is the “allowable” strength of each fiber type that can be guaranteed with 95% certainty? Assume a normal distribution of strength.

E11.5. Injection-molded chopped glass/epoxy composite panels have a mean in-plane strength of 220 MPa with a standard deviation of 10 MPa. Similarly processed jute–epoxy composite panels have a mean in-plane strength of 200 MPa with a standard deviation of 30 MPa. What is the “allowable” in-plane strength of each panel type that can be guaranteed with 99.7% certainty? Assume a normal distribution of strength.

E11.6. Use data read from Fig. 11.4 to estimate the thickness of a sandstone wall required to give a thermal delay time of 12 hours.

E11.7. What are the thermal characteristics of a straw-bale wall construction? Read the approximate thermal conductivity and thermal mass from Fig. 11.4. The insulating ability or *thermal resistance* of a wall is measured by its R value, equal to its thickness (in meters) divided by its thermal conductivity (in $\text{W/m}\cdot\text{K}$). What is the R value of a 200-mm straw-bale wall?

E11.8. The table lists the thermal properties of rammed earth (adobe). If an adobe house has walls 250 mm thick, how long will it take before the

interior starts to heat up after the exterior is exposed to a sudden rise in temperature as the desert sun rises?

Rammed earth (adobe)	Value
Density	1950 kg/m ³
Specific heat	870 J/kg•K
Thermal conductivity	0.6 W/m•K

E11.9. The table lists the thermal properties of ice. If a shelter is constructed out of ice blocks 300 mm thick, how long will it take the interior temperature to start changing after the exterior is exposed to the icy blast of an Arctic blizzard?

Ice property	Value
Density	925 kg/m ³
Specific heat	2100 J/kg•K
Thermal conductivity	2.1 W/m•K

E11.10. A maker of high-density polyethylene (HDPE) kitchen implements wishes to explore substitution with bio-plastics. To avoid major redesign, the specific stiffness and strength of the substitute must not differ from that of HDPE by more than $\pm 40\%$. Use the specific stiffness/specific strength chart of Fig. 11.6 to identify possible candidates.

E11.11. How does the specific strength of flax compare with that of Dacron? How do their carbon footprints compare? Use Figs. 11.10 and 11.12 to find out.

E11.12. Seatbelts are webbing woven from fiber. The function of a car seatbelt is to restrain the occupant in case of collision and to absorb the kinetic energy of his or her body. Fig. 11.11 of the text plots the energy-absorbing capabilities of fibers. Which synthetic fiber has the highest energy-absorbing ability? Which natural fibers have comparable energy-absorbing qualities?



Answer. Dacron has the highest energy-absorbing capacity of the fibers show in Fig. 11.11. (Real seatbelts are made of nylon or Dacron.) Spider silk has remarkable ability to absorb energy but is impractical in other ways. Silkworm silk is a possibility (and was the standard material for parachutes in an earlier era) but it is expensive. Wool looks like a viable alternative.

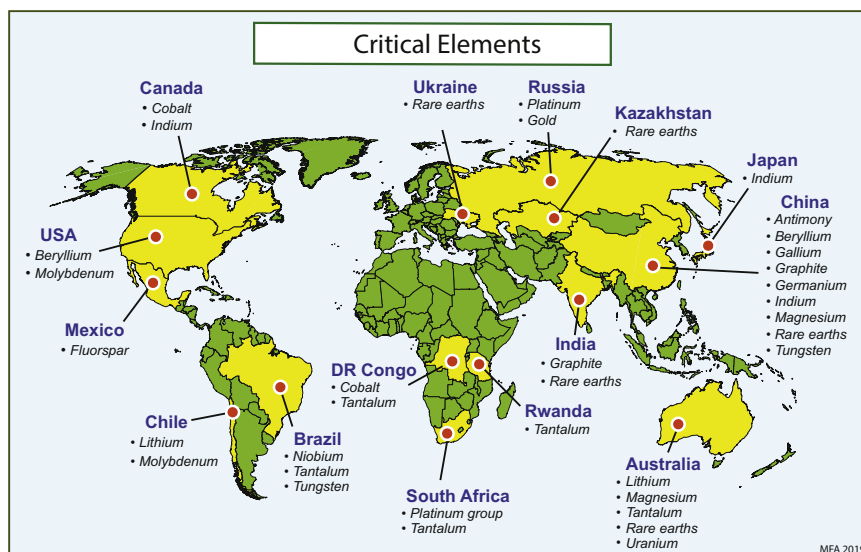
E11.13. Parachutes have a long history. Leonardo da Vinci designed one but did not use it. Real parachutes date from 1500, long before powered flight. In the intervening years, the material of choice for parachutes has evolved from cotton to silkworm silk, then nylon and Terylene, now Kevlar or even the super-fiber Zylon. Parachutes require fibers that are strong and light. Plot the progression of material choice on a copy of the specific strength chart for fibers, Fig. 11.11 of the text.



E11.14. Explore Fig. 11.16 showing the specific strength and modulus of natural composites to identify those that can offer the best combination of both.

E11.15. It is proposed to replace the steel door skins (outer panels) of a particular model of car with composite skins made from 40% ramie fibers in a phenolic matrix. If all the fibers lie in the plane of the sheet and, on average, 50% of them contribute to stiffness and strength in any in-plane direction, what approximate in-plane modulus and strength could be expected? Use a simple rule of mixtures to calculate upper bounds for both. Data for ramie and phenolics are listed in Appendix A, Tables A9 and A3.

Criticality and supply-chain risk



CONTENTS

- 12.1 Introduction and synopsis
- 12.2 Critical materials
- 12.3 Supply-chain risk
- 12.4 Managing risk
- 12.5 Summary and conclusions
- 12.6 Further reading
- 12.7 Exercises

12.1 Introduction and synopsis

A “critical” material is one that you need but may find hard to get. At a national level, a “critical” material is one that plays a key role in the economy and security of a nation, but has a supply chain that may be constrained or unstable. At the level of an industrial enterprise, the perception of criticality is more product-centric, focusing on the supply risk for the elements in the company’s product range and considerations of viable substitutes if these become unavailable.

There is an environmental dimension to all this. Action to limit climate change is driving the growth of technologies that rely on the rarer elements of the periodic table. Wind turbines use rare-earth magnets. Solar cells depend on indium, gallium, and germanium. Exhaust-cleaning catalytic converters contain platinum, palladium, and rhodium. Electric vehicles draw power from batteries dependent on lithium, cobalt, and rare earths.

Critical elements and the principal countries that supply them.

Which materials appear on the national critical material lists? Why? And what actions can be taken to ensure access to them? This chapter explores these questions.

12.2 Critical materials

Materials today are sourced and traded globally. The ores and feedstock needed to make some of them are widely distributed, allowing a free market to operate smoothly. Others, however, are geographically more restricted; the nations from which they come may limit supply for economic or political reasons; and social instability or conflict there or in neighboring states may interrupt the supply completely. The supply chain of cobalt, for instance, was disrupted recently by war in the Democratic Republic of the Congo, and that of rare-earth metals has not operated smoothly in the recent past because of monopoly constraints that led to unstable pricing.

Materials that are important for national security or economic growth are classified as critical if access to them could be limited.¹ Governments draw up lists of these critical materials and develop strategies to ensure supply by negotiating trade deals, seeking new sources, or stockpiling. The lists are not identical because “criticality” depends on the needs and domestic resources of the nation, but they have a great deal in common. Those that appear in US and EU lists are shown in Table 12.1. The table and the cover image of this chapter show where they come from. The lists act as warnings, alerting manufacturers that dependence on them could carry supply-chain risk. Many of these risks feature in the business section of today’s newspapers and news reports. We shall draw on these to illustrate the concerns.

Since the 1990s we have become increasingly dependent on a large number of these elements. As an example, a phone of the 1960s contained just nine metals for the frame, conductors, magnets, springs, and contacts, plus the carbon, hydrogen, and nitrogen of the plastic casing (Fig. 12.1). Mobile communication devices of today contain over 50 elements² (half the periodic table), of which more than half appear on “critical” lists. The picture, for almost all consumer electronics, for communication systems and transport, and (above all) for defense and security-related equipment, is similar.

¹The US government defines critical materials like this: “A critical mineral is a material essential to the economic and national security of the United States, the supply chain of which is vulnerable to disruption and that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy or our national security.”

²<https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/>.

Table 12.1 Elements classed as critical by the US or EU administration, 2018

Element	Principal source	Critical applications
Aluminum	China (42%)	Light alloys, aircraft, vehicles, power transmission lines
Antimony	China (87%)	Lead-acid batteries, ammunition
Arsenic	China (79%)	Displays, LEDs, lasers, microwave communications (GaAs semiconductors)
Beryllium	USA (90%)	Satellite communications, beryllium metal for aerospace (Cu–Be alloys)
Bismuth	China (82%)	Pharmaceuticals, lead-free solders
Cesium and rubidium	Canada	Global positioning satellites, night-vision devices
Chromium	South Africa (55%)	Jet engines (superalloys), stainless steels, high-temperature alloys
Cobalt	D.R. Congo (64%)	Jet engines (superalloys), rechargeable batteries
Gallium	China (85%)	Radar, LEDs, smartphones, solar cells
Germanium	China (67%)	Infrared devices, fiber optics, solar cells, smartphone screens
Graphite (natural)	China (69%)	Rechargeable batteries, body armor, nuclear reactors
Hafnium	France (43%)	Superalloys, turbines, control rods in nuclear reactors
Helium	USA (73%)	Cryogenics (magnetic resonance imaging), lighter-than-air craft
Indium	China (57%)	Flat-panel displays, touch screens (In–Sn oxide), solders
Lithium	Chile (42%)	Rechargeable batteries, aluminum–lithium alloys for aerospace
Magnesium	China (87%)	Light alloys, incendiary countermeasures for aerospace
Manganese	China (20%)	Steels, lightweight alloys
Niobium	Brazil (83%)	High-strength steel for defense, transport, and infrastructure
Platinum-group metals (Pt, Pd, Rh, Ru, Ir, Os)	South Africa (83%)	Catalysts, exhaust emission control, superalloys for jet engines

(Continued)

Table 12.1 [Continued]		
Element	Principal source	Critical applications
Rare-earth elements: Ce, Y, Nd	China (94%)	Guidance systems, lasers, fiber optics, high-field magnets
Rhenium	Chile (51%)	Jet engines (superalloys), catalysts
Scandium	China (66%)	Lightweight alloys for aerospace and defense, fuel cells
Strontium	Spain (44%)	Aluminum alloys, permanent magnets, electronics
Tantalum	Rwanda (31%)	Capacitors in cellular phones, jet engines (superalloys)
Tellurium	China (40%)	Infrared devices (night vision), solar cells
Tin	China (33%)	Solder, flat-panel displays, touch screens (In–Sn -oxide).
Titanium	China (12%)	Superalloys, airframes, submarines, armor
Tungsten	China (84%)	Cutting and drilling tools, catalysts, jet engines (superalloys)
Uranium	Kazakhstan (42%)	Nuclear applications, medical applications
Vanadium	China (53%)	Superalloys, airframes, high-strength steels
Zirconium	Australia (45%)	Thermal barrier coating in jet engines, nuclear applications

Sources: USGS 2018: <https://pubs.usgs.gov/of/2018/1021/ofr20181021.pdf>. <https://www.federalregister.gov/documents/2018/05/18/2018-10667/final-list-of-critical-minerals-2018>. EU 2017: <https://ec.europa.eu/transparency/regdoc/rep/1/2017/EN/COM-2017-490-F1-EN-MAIN-PART-1.PDF>. CES EduPack compilation 2018: www.grantadesign.com/education.

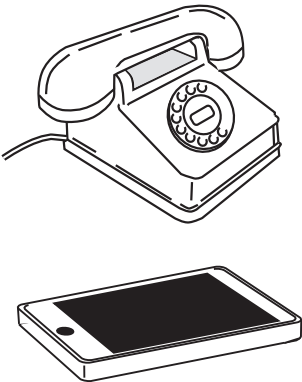


FIGURE 12.1 Phones, 1960 and 2020.

Newsclip: “We need to get serious about ‘critical materials’.”

The US needs to widen its consideration of critical materials past a limited understanding of security.

Scientific American, June 2019

More studies of recovery, recycling, and substitution of critical elements are vital for US economic interests.

Newsclip: “UK could be held to ransom over electric cars.”

The Times, June 6, 2019

The UK’s 2035 target for electric cars requires the import of as much cobalt as is currently consumed by all Europe, according to Security of Supply of Mineral Resources, a government-funded body, who warn that the supply of cobalt is controlled by a small number of unstable countries.

Newsclip: “Hunt for elements to undermine China.”

The US faces being cut off from natural resources crucial to modern life: smartphones, guidance systems, electric cars and more.

The Times, August 26, 2019

For two decades, starting in the 1960s, the Mountain Pass mine in California produced most of the world’s rare earths. In the decades since, China has consolidated control of both mining and processing, and acquired rights to deposits in Africa. It now controls over 90% of the supply. China has threatened to restrict exports if trade relations with the United States worsen.

Newsclip: “Japan crisis hurts uranium miners.”

Uranium miners are suffering at the hands of investors amid fears that Japan’s nuclear crisis (the melt-down at the Fukushima plant) could restrict the growth of atomic energy.

The Times, March 18, 2011

In March 2011, uranium share prices fell 35%, takeovers were canceled, China suspended approval permits for new reactors, and Germany indicated it would phase out its reactors altogether. These are examples of demand-side breakdown. The problems are not always on the supply side.

12.3 Supply-chain risk

A century ago, developed nations sourced materials locally or from colonies or dependencies under their control. Today, materials are sourced and traded globally

between independent nations, many with their own developed or developing manufacturing base. This dependence on a global supply chain brings risks that escalate as affluence and demand grow. As we have just seen, these concerns prompt nations to classify risk-prone materials with high commercial or strategic importance as “critical.” Many of these critical materials come from one or a very few source nations, exposing their supply chain to further restriction for geo-economic or geopolitical reasons. These and other supply-chain risks cause concern at the corporate as well as the national level (Table 12.2).

Sustainability in a material-dependent industry, from a corporate viewpoint, means ensuring reliable access to affordable raw materials. Surveys³ of CEOs of manufacturing companies across Europe found that 80% of them saw future raw-material shortages and rising material prices as threats to their business. Similar surveys highlight the concerns created by the expanding body of legislation that restricts or bans, for health or environmental reasons, an increasing range of materials and chemicals. Further legislation sets new standards for ethical material sourcing, product safety, consumer protection, and responsibility for materials at end of product life. Complying with this legislation can be burdensome and expensive, but failure to comply can compromise the ability to continue trading.⁴ The competencies of a materials engineer today have to include not only technical skills but also the ability to manage risk.

Table 12.2	Supply-chain risk
	Abundance risk
	Price volatility risk
	Monopoly of supply risk
	Geopolitical risk
	Regulatory risk
	Export Restriction risk
	Conflict minerals risk
	Corporate social Responsibility risk

³Government Office for Science UK (2013), “Future of manufacturing: a new era of opportunity and challenge for the UK—summary report” London, available online: <https://www.gov.uk/government/publications/future-of-manufacturing/future-of-manufacturing-a-new-era-of-opportunity-and-challenge-for-the-uk-summary-report>.

⁴Granta Design (2013), “Enabling product design and development in the context of environmental regulations and objectives,” a white paper, available online: <http://www.grantadesign.com/emit/>.

We explore these in a little more depth in the rest of this section.

Abundance risk. How much of everything have we got? Fig. 2.1 showed the abundance of the elements in the earth's crust. The range is enormous: a factor of 10^{10} from the lowest (iridium) to the highest (oxygen). The lowest economically viable concentration for extraction follows a similar pattern. The price follows an inverse picture.

Views are sometimes expressed that we are about to “run out” of some of the less-plentiful elements. That does not look like a near-term problem—the earth's crust is large and deep. But there is, nonetheless, a problem with any element that occurs only in very low concentrations: the energy it takes to expose, mine, and crush the rock in which it lies. One kilogram of the richest iron ores contains almost 0.5 kg of iron, but to get 1 kg of platinum requires the mining of about 500 tonnes of ore. If energy prices rise, the less-abundant elements are the most vulnerable.

Newsclip: “Are global lithium deposits enough to meet electric car demand?”

***The New York Times*, July 28, 2011**

A science correspondent questions the supply chain for lithium if electric cars become the norm.

Price volatility risk. Over much of the past century material supply was not (with occasional exceptions) a major concern. Trade tended to be national rather than global. Material prices, in real terms, were static or falling (Fig. 12.2, left-hand side).

Beginning around 2000, metal prices have become more volatile and have risen faster than inflation (Fig. 12.2, right-hand side). Metals commodity prices are more volatile than those of other consumer goods because of what economists call *price inelasticity*: the inability of the market to respond quickly to changes in demand. If, as an example, the demand for copper suddenly surges (as it did around 2005), the global production cannot respond immediately. Mines must be expanded and new processing plants built, a response that, typically, takes 3 years. The price of copper rose by a factor of 4 in 2007 and again in 2011, caused in part by strikes in the copper mines of Chile and a surge in demand from China. The price of rare earth elements rose by a factor of more than 10 when China imposed export restrictions in 2011. The supply of cobalt was disrupted in 2007 and again in 2018 by war in the Democratic Republic of the Congo, causing the price to treble. Fig. 12.3 illustrates how the price spikes when demand exceeds supply, falling back to a base level (here, about \$36/kg) after an adjustment period of, typically about 3 years.

Newsclip: “Mine strike to drive up platinum price”

***Eyewitness News*, March 6, 2014**

Interruption of a supply chain has immediate economic consequences.

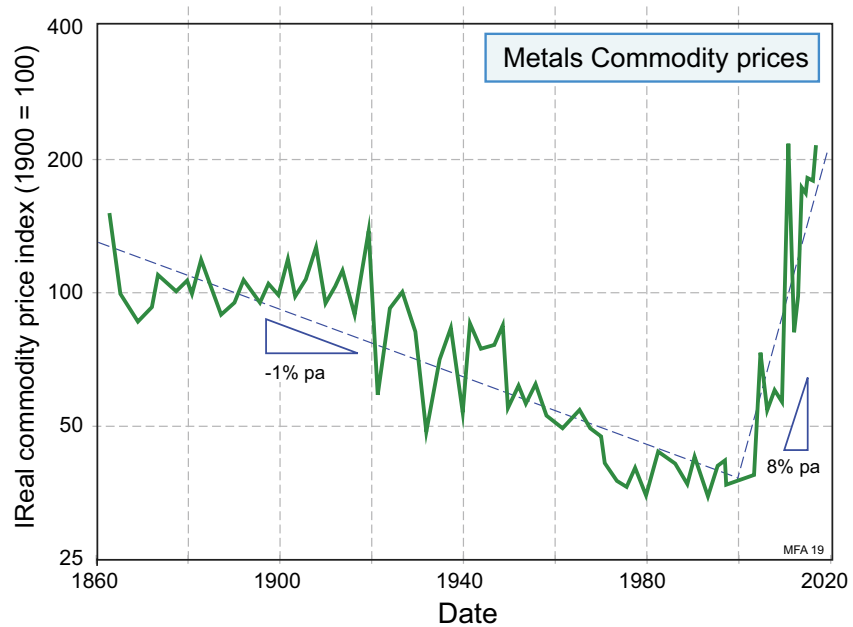


FIGURE 12.2 The movement of the price of a portfolio of metals. (Data from the World Bank, and the Economist, Material Risk.com.)

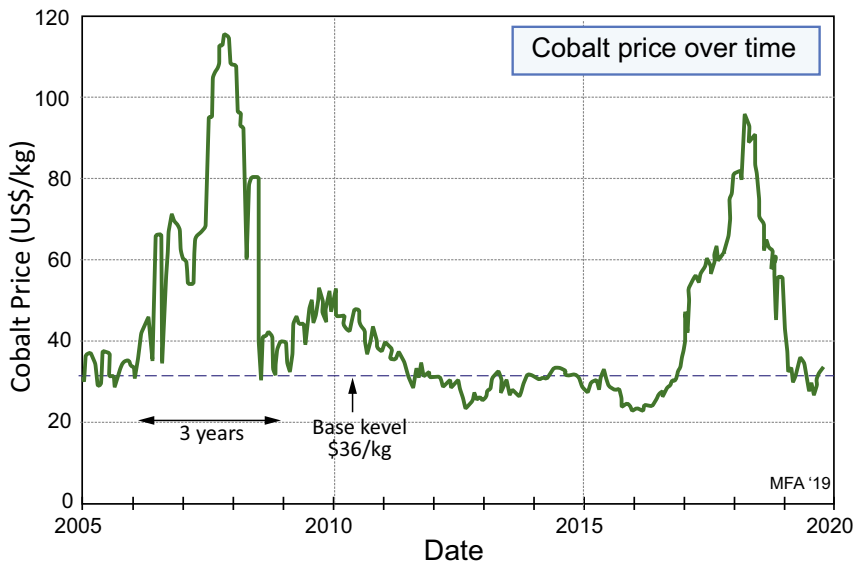


FIGURE 12.3 The price of cobalt over a 15-year period. (Data from [Informine.com](#).)

Monopoly of supply and geopolitical risk. The cover image of this chapter identifies the main countries of origin of the critical materials listed in Table 12.1. If one of these controls a large fraction (half, say) of the global supply of a material, the market in that material is unbalanced and the potential for disruption exists. The Herfindahl–Hirschman Index (HHI) is a measure of the risk when the supply of a material is controlled by one or a very few players. It is defined as:

$$\text{HHI} = \sum_{i=1}^n f_i^2, \quad (12.1)$$

where f_i is the fraction of the market sourced from nation i and n is the total number of source nations.

The value of the HHI ranges from 0 to 1. If one nation has a complete monopoly of the market, the $\text{HHI} = 1$. If two have equal shares, the $\text{HHI} = 0.5^2 + 0.5^2 = 0.5$. If the market is served by a large number of source nations, all of which have only a small fraction, the HHI tends toward 0. A value below 0.1 is an indicator of an unconstrained market. A value above 0.25 suggests supply-chain concentration. Fig. 12.4 shows the HHI for 20 elements that are classified as critical; most of them have a value exceeding 0.3. Dependence on materials with supply-chain concentration carries the risks of monopoly action, disruption of supply, and volatile pricing. Like blood pressure, it is good to keep your HHI low.

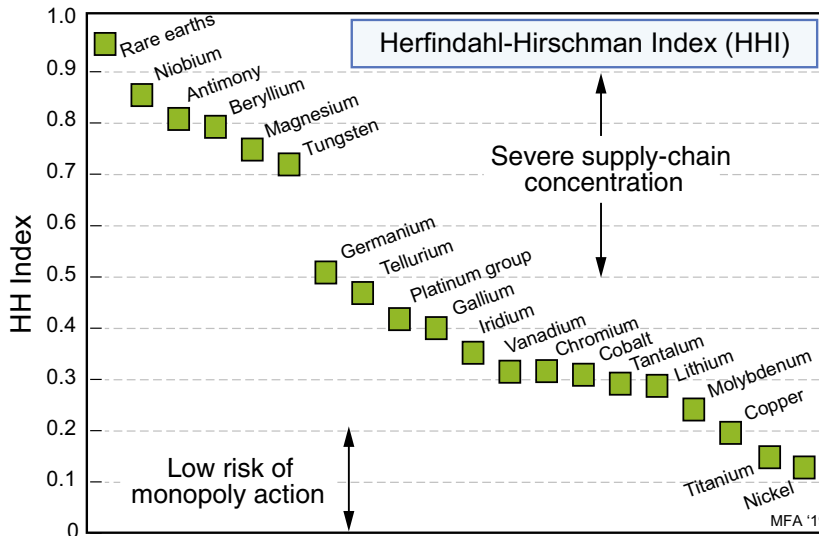


FIGURE 12.4 The Herfindahl–Hirschman Index for a number of critical materials. (Data from USGS, 2018.)

Newsclip “EU takes legal action against export restrictions on Chinese raw materials.”

China currently imposes a set of export restrictions, including export duties and export quotas, that limit access to the raw materials they produce for companies outside China. Following the successful legal actions in 2012 and 2014 on similar measures, this time the EU is focusing on restrictions concerning graphite, cobalt, copper, lead, chromium, magnesia, talcum, tantalum, tin, antimony and indium.

European Commission Press release, 19 July 2016

Legislation and regulatory risk. An expanding body of legislation, regulation, and standards addresses the impact of products and the materials they contain on the environment, human health, and society. Chapter 5 introduced some of them. They include the reporting and restriction of the uses of certain materials, energy usage, conflict minerals, and product disposal at end of life. Such legislation creates a considerable burden of compliance and reporting. It also creates risks by rendering key materials or processes obsolete or unobtainable. This is a particular risk for long-lived products such as aircraft. If the materials they contain become restricted, forcing substitution, requalification may be required—an expensive imposition.

To comply with this legislation, manufacturers must report the chemical background of the materials they use. Ordinary solder contains lead. Rechargeable batteries contain cadmium, and long-life, low-drain batteries contain mercury. All are unacceptable “heavy” metals that damage biosystems. Chromium plating involves toxic hexavalent chromium. Many polymers contain flame retardants or plasticizers, some recently banned, others on a waiting list. Increasingly, manufacturers must also take responsibility for materials at the end of product life. Legislation is already in place requiring manufacturers to take back electronic equipment, vehicles, and tires.

Restrictions can cross national borders. Japanese carmakers must comply with European or US legislation if they wish to sell their cars in those nations. In an era of globalization, national legislation has global implications.

Newsclip: “To universal surprise, the National Assembly (of France) bans phthalates”

***Le Figaro*, May 4, 2011**

Makers of products using phthalate-plasticized poly(vinyl chloride) are abruptly deprived of their core material.

Export restriction risk. Mineral resources are a huge potential source of income for the countries that have them. The mining sector creates relatively little employment in the countries where extraction occurs. Seeking to create more jobs, some countries restrict the export of unprocessed minerals to encourage the creation of higher-value downstream processing jobs in the domestic market (Table 12.3). Export restrictions are used to meet other objectives: to generate revenue for the government, to control the export of illegally mined products, to limit environmental damage, or to give competitive advantage to domestic industries.

Studies suggest that export restrictions are not the best way to achieve these policy objectives; in some cases, they can do the opposite (OECD, 2019). Despite this, many nations restrict export of raw materials such as minerals, metals, and wood. In some emerging economies, most minerals exports are restricted (Fig. 12.5). Restrictions can be imposed with little warning, disrupting material

Table 12.3 Materials export restrictions

Export prohibition	(P)
Export quotas	(Q)
Export tax	(T)
Restricted licensing	(L)



FIGURE 12.5 Nations that impose export restriction on materials.

supply chains and driving up prices, at least in the short term. They represent another source of risk.

Newsclip: “Indonesia ban on raw mineral exports threatens nickel shake-up.”

Reuters, January 10, 2014

Developing nations increasingly take control of their natural resources.

Conflict risk and corporate social responsibility. Increasingly, ethical concerns inhibit the purchase of minerals from nations in which the proceeds might be used to fund conflict. The US Dodd–Frank act creates trade barriers with nations in which ongoing conflict compromises human rights. Many of these troubled nations are mineral rich (Fig. 12.6). The short-term loss of production drives up prices. This in turn stimulates expansion of production in other nations and the search for substitutes, ultimately restoring the balance—but (as already mentioned) this rebalancing can take three or more years.

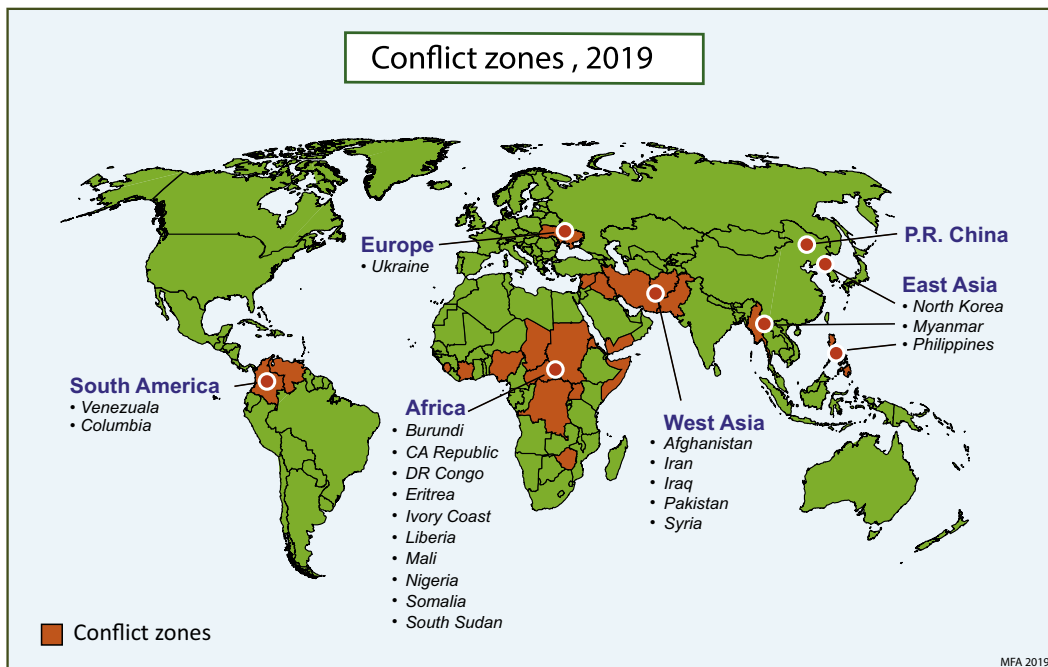


FIGURE 12.6 Nations with ongoing conflicts.

Newsclip: “An ugly truth behind ‘ethical consumerism.’”

The Dodd–Frank Act requires American companies to disclose if their tin, tungsten, tantalum or gold came from Congo and also to conduct due diligence to mitigate risks that these minerals could be fuelling armed groups. The reality is that conflict-minerals sites are not controlled by the government and are exploited by armed groups.

Washington Post, April 19, 2018

Conflict minerals find ways to market that bypass national governments.

Newsclip: “Conflict minerals rule poses compliance challenge.”

Journal of Accountancy, April 2013

Newsclip: “Auto industry steels itself for conflict materials rule.”

Automotive News, September 24, 2013

Newsclip: “Apple plans to cut the ‘conflict minerals’ in its devices.”

The Times, February 14, 2014

The manufacturing sector reflects on the consequences of the Dodd–Frank act.

Newsclip: Resources, a blessing or a curse? “Miner pays Aborigines \$2bn to gain land rights.”

Rio Tinto has struck a \$2 billion, 40 year deal with five Aboriginal groups to secure access to their land in resource-rich Western Australia.

The Times, June 4, 2011

Will the deal lift living standards for these Aborigines? Since 1990, the petroleum industry has invested more than \$20 billion in exploration and production activity in Africa, but the wealth has destroyed traditional lifestyles and generated armed conflicts. Diamonds and gold have brought similar societal breakdown. It is a paradoxical fact that countries and regions with an abundance of natural resources, particularly minerals and oil, tend to have less economic growth and worse development outcomes than countries with less—an effect known as the *resource curse*.

Changing expectations of corporate responsibility. The Dodd–Frank act is an example of the imposition of ethical standards by government. Increasingly

consumers, often supported by shareholders and nongovernmental organizations, urge companies to examine the environmental and social impact of their processes and products. The United Nations encourages sign-up to the 10 principles of its Global Compact,⁵ a set of ethical standards for sustainability reporting. The vision is to promote a sustainable global economy in which organizations manage their economic, environmental, and social performance and governance in ways consistent with the common good. Company performance is monitored by independent organizations that award “sustainability indices” rankings that are now of considerable influence. Prominent among them are the FTSE4Good index, the Dow Jones Sustainability Index, and the Business in the Community index (FEE 2008). Strong performance in this area can be turned to competitive advantage, but environmental claims made on product labels must stand up to scrutiny. Signs of “green-washing”—making unsubstantiated claims of good environmental and ethical behavior—are now examined closely; the US Federal Trade Commission,⁶ for example, sets guidelines for making environmental claims. Rigor and quantitative validation are now essential in this area.

All of these issues restrict unfettered access to materials. Environmental responsibility and regulatory compliance in product design and development are no longer “optional extras,” they are business imperatives.

12.4 Managing risk

Dependence on a material containing elements flagged as “critical” implies the possibility of supply-chain disruption. What can be done about it? There are a number of options:

- Short-term fluctuations in availability and price can be damped by building reserves or by negotiating long-term supply contracts. Manufacturing nations increasingly compete for exclusive rights to mineral resources worldwide to safeguard their industrial capacity.
- Longer-term supply constraints can be mitigated by redesign to use critical materials more efficiently and by increasing take-back, recycling, and reuse to keep them in service.
- Damaging price inflation can be countered by seeking substitutes, and here there is scope for forward planning to build a knowledge base of viable substitutes⁷ and their suppliers.
- Legislation that creates unnecessary barriers to the sourcing and use of materials can be confronted with reasoned argument and lobbying.

⁵<https://www.unglobalcompact.org/>.

⁶US Federal Trade Commission: <https://www.ftc.gov/enforcement/rules/rulemaking-regulatory-reform-proceedings/green-guides>.

⁷Graedel et al (2013).

12.5 Summary and conclusions

Growing population and global affluence drive up demand for materials and give mineral-rich nations greater bargaining power. Environmental legislation restricts the use and disposal of an increasing number of materials. Unstable government and armed conflict can interrupt supply. Pressure for ethical corporate behavior further limits available sources (Fig. 12.7). The combination of these has caused material prices to rise faster than wealth for the first protracted period in the past 100 years.

The role of the materials engineer in a 21st-century materials-intensive enterprise is now likely to involve issues such as:

- anticipating material supply-chain constraints and their causes and probable duration, particularly where critical materials are involved;
- precautionary exploration of substitutes for materials important to the enterprise for which they work;
- adapting to, and complying with, environmental and other material-related legislation; and
- helping the enterprise to adapt to a more circular materials economy, retaining full-life ownership of the materials of their products, and maximizing reuse and recycling.

What is a circular materials economy? That is the subject of the next chapter.

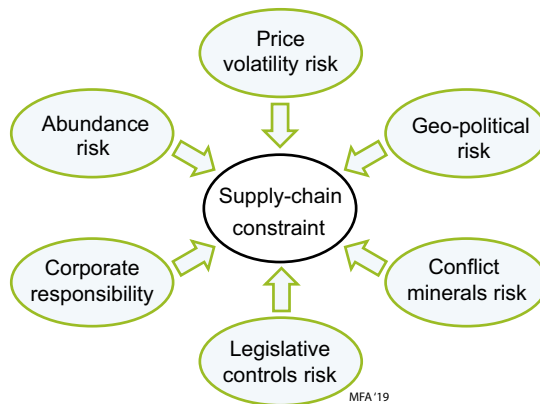


FIGURE 12.7 *Material supply-chain constraints.*

12.6 Further reading

- Ashby M.F. and Vakhitova, T. (2014) "Material risk and Corporate Sustainability – a White Paper, Granta Design, Cambridge, UK. www.grantadesign.com.
- Center for Sustainable Systems, University of Michigan (2016) "Critical Materials Factsheet." Pub. No. CSS14-15. <http://css.umich.edu/factsheets/critical-materials-factsheet>.
- Dow Jones Sustainability Index (2012). https://en.wikipedia.org/wiki/Dow_Jones_Sustainability_Indices (A ranking of Corporate performance based on sustainability factors that are financially relevant for businesses.)
- Ethical Corporation (2013) "Full product transparency is the future of reporting", <http://www.ethicalcorp.com/communications-reporting/full-product-transparency-future-reporting>. (Standards for reporting ethical manufacture and sourcing.)
- Graedel, T.E., Harper, E.M., Nassar, T.N., and Reck, B.K. "On the materials basis of modern society", Proceedings of the National Academy of Sciences, 1312752110 (2013).
- Jaffe, R. and Price, J. (2010) "Critical elements for new energy technologies", American Physical Society Panel on Public Affairs (POPA) study, American Physical Soc. USA. (*Critical materials for energy technology*.)
- Leader, A., Gaustad, G., and Babbitt, C. (2019) "The effect of critical material prices on the competitiveness of clean energy technologies", Mater Renew Sustain Energy 8: 8. <https://link.springer.com/article/10.1007/s40243-019-0146-z>.
- Rankin, W.J. (2011), "Minerals, Metals and Sustainability – meeting future material needs", CSIRO Press. (A thorough and revealing analysis of materials, sustainable development, and the Australian mining industry.)
- MIT (2016) "The future of Strategic Natural Resources", <https://web.mit.edu/12.000/www/m2016/finalwebsite/problems/raremetals.html>.
- OECD (2019) "How exports of mineral commodities contribute to economy-wide growth", <http://www.oecd.org/trade/topics/trade-in-raw-materials/>.
- USGS (2002) Circular (2112) "Materials in the economy –material flows, scarcity and the environment", by L.W. Wagner, US Department of the Interior (www.usgs.gov). (A readable and perceptive summary of the operation of the material supply-chain, the risks to which it is exposed, and the environmental consequences of material production.)
- World GDP per capita over time: <https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html>. (A striking animation of the way in which the GDP of nations has evolved.)

12.7 Exercises

E12.1. The US Geological Survey Mineral Statistics. The USGS publishes annually updated statistics for the world production of key elements. That for lithium can be accessed here: <https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mcs-2019-lithi.pdf>.

Use it to make a table of lithium production by nation. Which nation produces the most? By what factor?

E12.2. The British Geological Survey (BGS) risk list. The BGS assigns a supply-risk ranking for elements of particular economic value: [file:///C:/Users/User/Downloads/RiskList2015%20\(2\).pdf](file:///C:/Users/User/Downloads/RiskList2015%20(2).pdf).

- (a) Which elements are assigned the highest risk by the BGS?
- (b) What is the risk assigned to lithium?

E12.3. What is the “resource curse”? Use the Internet to assemble a short description.

E12.4. What does “resource imperialism” refer to? Use the Internet to assemble a short description.

Tungsten-producing nation	Tonnes/year, 2018
Austria	980
Bolivia	1000
China	67,000
Portugal	770
Russia	2100
Rwanda	830
Spain	750
United Kingdom	900
Vietnam	6000
Other countries	1400
World	82,000

USGS Mineral Commodity Summaries.

E12.5. The HHI is a measure of risk when the supply of a material is controlled by one or a very few nations. It is defined in Eq. (12.1) of the text as:

$$HHI = \sum_{i=1}^n f_i^2,$$

where f_i is the fraction of the market provided by nation i and n is the number of nations.
The table lists the world production of tungsten by nation. Calculate the HHI for tungsten based on these values. Does the result suggest supply-chain constraint?

Manganese-producing nation	Thousand tonnes/year, 2018
Australia	3100
Brazil	1200
China	1800
Gabon	2300
Ghana	850
India	770
Kazakhstan	170
Malaysia	510
Mexico	220
South Africa	5500
Ukraine	740
Other countries	940
World	18,000

USGS Mineral Commodity Summaries.

E12.6. The HHI is defined in Exercise E12.5. The table lists the world production of manganese by nation. Calculate the HHI for manganese based on these values. Does the result suggest supply-chain constraint?

E12.7. Sourcing cobalt. You are consulted by a steelmaker who wishes to make a special steel with 5% cobalt content. What can you tell them about the risk to the supply of cobalt? Use the USGS Minerals Commodity Yearbook (<http://minerals.usgs.gov/minerals/pubs/commodity/myb/>) to research the nations from which cobalt is sourced. Use the Internet to research further the stability and governance of the main producing nation (www.govindicators.org). Include the HHI in your report.

E12.8. Cutting tools. A company specializing in road repair relies on cobalt-bonded tungsten–carbide cutting tools for stripping road surfaces. The CEO of the company is considering investment in a supplier of these cutting tools

to ensure supply. Both cobalt and tungsten appear on the European Union list of critical materials. The HHI for tungsten is 0.77; that for cobalt is 0.42. Both values are high, tungsten particularly so, indicating severe supply-chain concentration. This carries the risk of price fluctuations, confirmed in the case of cobalt by Fig. 12.3 of the text. A search reveals that the tungsten price has been less volatile; it has risen by a factor of 1.5 between 2010 and the present day. The CEO of the company is concerned about this and asks for a study of the risk that investment in the cutting-tool company might carry. Investigate what substitutes could be found if the supply of cobalt or tungsten were restricted.

E12.9. Germanium has unique optical, electrooptical, and semiconducting properties used in fiber optics, lenses for infrared optics, electronics, solar cells, and light-emitting diodes. It is listed as a critical material. Use the USGS Minerals Commodities summaries, available at <https://www.usgs.gov/centers/nmic/mineral-commodity-summaries>, to investigate why it is given this classification and what substitutes could be found if the germanium supply were restricted.

E12.10. Platinum is listed as a critical material. Investigate why it is given this classification and what substitutes could be found if the platinum supply was restricted.

E12.11. Rhodium is listed as a critical element. Investigate why it is given this classification and what substitutes could be found if the rhodium supply were restricted.

E12.12. Copper indium gallium selenide (CIGS)–based solar cells offer the highest conversion efficiency for large-scale, thin-film solar cells with efficiencies exceeding 16%. Production for commercial use is expanding rapidly. Which of the CIGS elements are classified as critical? Why?

E12.13. Fuel cells use yttrium–platinum alloys to catalyze the following reaction:



Platinum is a critical element. What about yttrium?

Circular materials economics



CONTENTS

- 13.1 Introduction and synopsis
- 13.2 The ecological metaphor
- 13.3 Resource husbandry—history and scale
- 13.4 A circular materials economy
- 13.5 Creating a more circular materials economy
- 13.6 Getting real: how circular can we get?
- 13.7 Summary and conclusions
- 13.8. Further reading
- 13.9 Exercises

13.1 Introduction and synopsis

The materials economy of today is largely linear. Our use of natural resources is characterized by the sequence *"take–make–use–dispose."* Materials progress from mine, through product, to landfill. Increasing population, rising affluence, and the limited capacity for the planet to provide resources and absorb waste argue for a transition toward a more circular way of using materials. When products come to the end of their lives the materials they contain are still there. Repair, reuse, and recycling (the three "Rs") can return these to active use, creating a

technological cycle that, in some ways, parallels the carbon, nitrogen, and hydrological cycles of the biosphere. Repair, reuse, and recycling are not new ideas; they have been used for centuries to recirculate materials and, in less-developed economies, they still are. But in developed nations they lost urgency as the cost of materials fell and that of labor rose, making all three Rs uneconomic. So what is novel about the contemporary push for a more *circular materials economy*? Haven't we been there before?

The answer, perhaps, is: an *attitude of mind*. As McDonough and Braungart, two vocal proponents of circular thinking, point out: waste is a symptom of design failure. Governments have sought to reduce waste by imposing take-back regulations, setting mandatory recycling targets, and requiring minimum service lives. They are a sort of chastisement: we are behaving badly; regulation carries the message that we should behave better. One reaction has been "efficiency" movements—eco-efficiency, material efficiency, energy efficiency. All are admirable but all seek to allow business as usual with reduced drain on natural resources (and sense of guilt) without any real change in behavior.

The "circularity" concept is a way thinking that looks not just for efficiencies but also for new ways to provide functions. The idea of deploying rather than consuming materials, of using them not once but many times, and of redesign to make this a reality has economic as well as environmental appeal. This chapter examines the background, the successes, and the difficulties of implementing a circular materials economy.

13.2 The ecological metaphor

Natural and industrial systems have some features in common but are strikingly different in others. Consider three.

The first: both the natural and the industrial systems transform resources, meaning materials and energy, to provide functionality. Nature does it through biological growth. Industry does it through manufacture. The plant kingdom captures energy from the sun, carbon dioxide from the atmosphere, and minerals from the earth to create carbohydrates and proteins; the animal kingdom derives its energy and essential minerals from those of plants or from other animals. The industrial system, by contrast, acquires most of its energy from fossil fuels and its raw materials from those that occur naturally in the earth's crust, in the oceans, and in the natural world.

The second similarity: both systems generate waste, the natural system through the metabolism and death of organisms, the industrial system through the emissions of manufacture and through the finite life of the products it produces. The difference is that the waste of nature is recycled with 100% efficiency, drawing on renewable energy (sunlight) and natural decay processes to return it to the ecosystem. The waste of industry is recycled much less effectively, requires nonrenewable energy (fossil fuels) to do so, and leaves a legacy of depleted resources and contaminated ecosystems.

The third similarity: both the natural and the industrial systems exist within a single global ecosphere. This ecosphere provides the raw materials and other primary resources, acts as a reservoir for waste, and provides the essential environment for life, meaning fresh water, a breathable atmosphere, tolerable temperatures, and protection from UV radiation. The natural system manages, for long periods, to live in balance with the ecosphere. Our present industrial system, it appears, does not. Are there lessons to be learned about managing industrial systems from the balances that have evolved in nature? Can nature give guidance, or at least provide an ideal?

Of the 92 usable elements of the periodic table, four are of central importance for life: carbon, nitrogen, hydrogen, and oxygen. They largely make up the carbohydrates, fats, and proteins on which life depends. To allow a steady state these elements must be constantly recycled around the ecosystem. The most important of these circular paths are the *carbon cycle*, the *nitrogen cycle*, and the *hydrological (water) cycle*. Subsystems have evolved that provide the links in the cycles and do so at rates that match, thus avoiding bottlenecks at which waste accumulates. Fig. 13.1 is a sketch of one of these, the carbon cycle. Carbon dioxide in the atmosphere is captured by green plants and algae on land, and by phytoplankton and other members of the aquatic biomass in water. Fungal and bacterial action enables decomposition of plants and animals when they die, returning much of the carbon to the atmosphere but also sequestering some as carbon-rich deposits of peat, gas, oil, coal, and, in the oceans, limestone, CaCO_3 .

The elements important for human-made products, by contrast, are far more numerous. Today, as we saw in Chapter 12, they include most of the elements of the periodic table. Carbon is one. The products that use it (in the form of coal, oil, or gas) eject most of it into the atmosphere as CO_2 . As industrial activity has grown, the rate of CO_2 emission has increased, but the natural subsystems that recycle it have not evolved at a matching rate (Fig. 13.2). When rates don't match, stuff piles up somewhere. Focusing on carbon again, this imbalance is evident in the steep rise of atmospheric carbon since 1850. The problem is more acute with other elements, the heavy metals, for example, for which no natural recycling mechanisms exist.

What do we learn? First, that industrial systems lack appropriate subsystems to close many of the recycling paths, and second, that where subsystems exist, there is an imbalance of rates. At base, however, there is a more fundamental difference: it has to do with metrics of well-being. That of nature is achieving *balance*, such that the system is in equilibrium. That of the industrial system is *growth*. Growth has become our measure for the well-being of businesses, nations, and society as a whole. An economy that is growing is "healthy," one that is static is "sick." The present-day model for economic growth carries with it the need for ever-increasing consumption of materials and energy and of waste creation. The characteristic that makes this system damaging for the environment is its insatiable appetite: the faster it ingests resources, the greater is the output of products and the better is its "health," even though this does not coincide with the health of the biosphere.¹

¹Frosch, cited by Guidice et al. (2006).

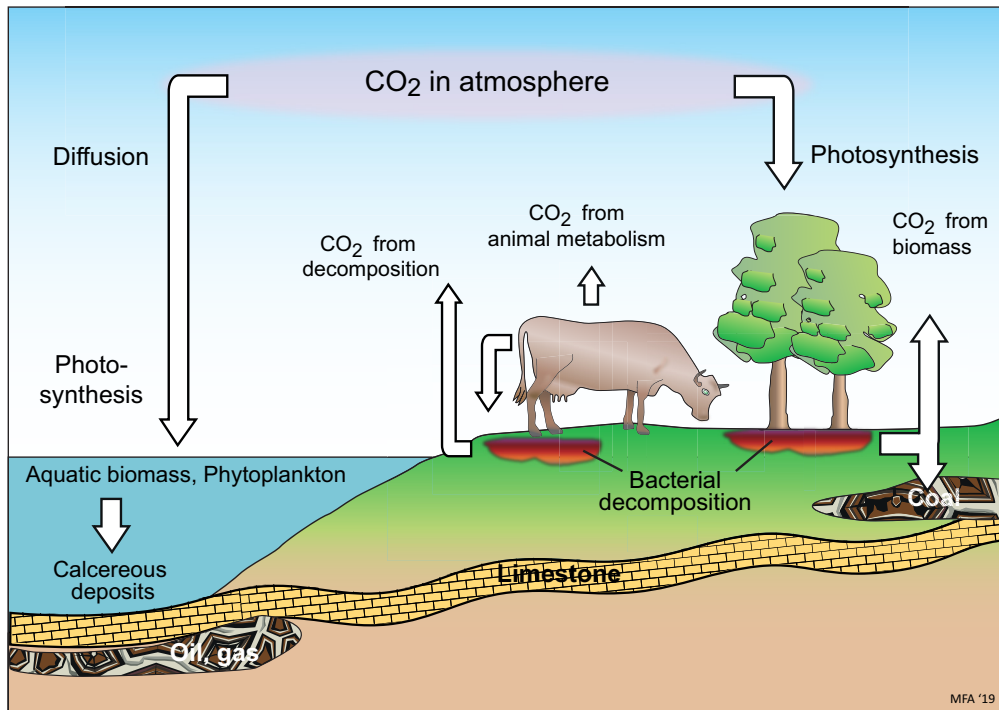


FIGURE 13.1 The carbon cycle in nature, showing some of the many subsystems that have evolved to transform resources.

The comparison, then, suggests an ideal: an industrial system in which the consumption of materials and energy and the production of waste are minimized, and the discarded material from one product or process becomes the raw material for another.

Newsclip: “A new consuming philosophy: reuse, remake, refrain.”

Advocates of collective consumerism oppose waste and want you to share your goods or just buy less.

Los Angeles Times, June 29, 2013

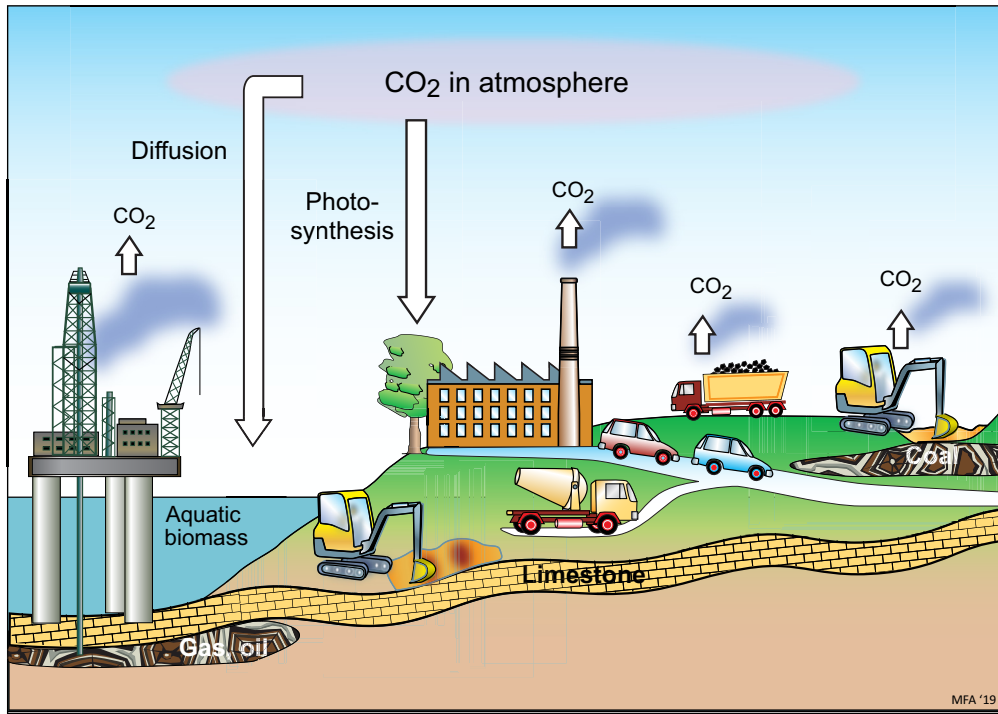


FIGURE 13.2 *The additional burden placed on the carbon cycle by large-scale industrialization.*

Newsclip: “Keep your old gadgets out of the trash.”

The New York Times climate correspondents argue for reuse or recycling of phones, computers, and televisions rather than dumping them.

***The New York Times*, April 3, 2019**

13.3 Resource husbandry—history and scale

Conserving resources is not a new idea, but ideas about the best way to do it have evolved with time (Fig. 13.3). The approach 60 years ago, “Wait until there’s a problem, then fix it if you have to,” has mutated into whole-life assessment and preemptive design, incorporated into national policy. This has gone hand-in-hand with a broadening of the timescale of thinking. The horizontal axis of Fig. 13.4 describes this timescale, ranging from that of the life of a product to that of the span of a civilization. The vertical axis describes the spatial scale, again ranging from that of the product to that of society as a whole. It has four nested boxes, expanding outward in conceptual scale, each representing an approach to thinking about the environment.

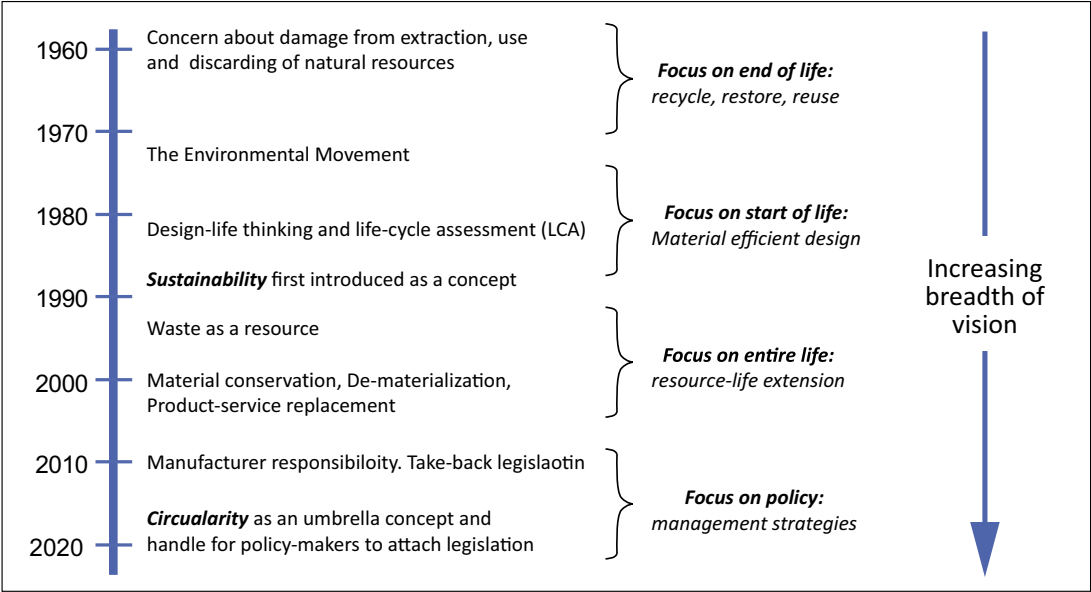


FIGURE 13.3 Material husbandry: a timeline. (Adapted from Blomsma and Brennan (2017).)

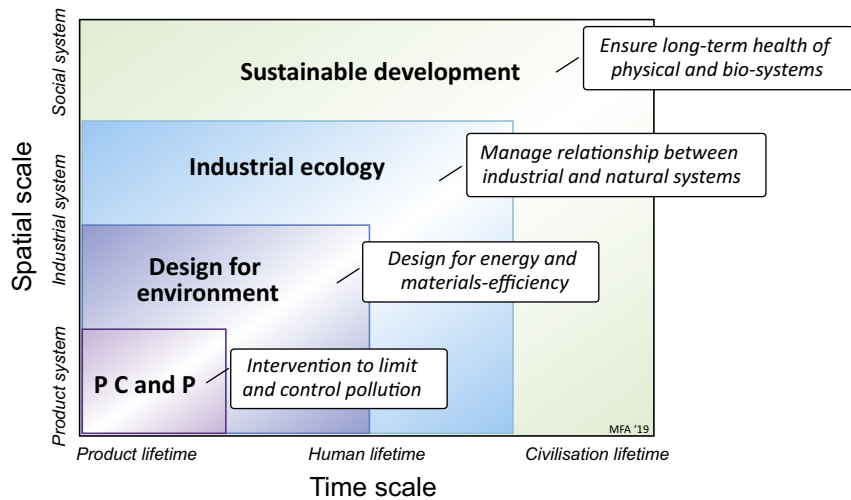


FIGURE 13.4 Approaches, differing in spatial and temporal scale of thinking, about industrialization and the natural ecosystem. PC and P, pollution control and prevention. (Adapted from Coulter et al. (1995).)

The least ambitious of these—the smallest box—is that of *pollution control and prevention*. This is intervention on the scale and lifetime of a single product and is frequently a cleanup measure. Taking transport as an example, it is the addition of catalytic converters to cars, a step to mitigate an identified problem associated with an existing product or system.

The next box is *design for the environment*. Here the time and spatial scales include the entire design process; the strategy is to foresee and minimize the environmental impact of product families at the design stage, balancing them against the other objectives of performance, reliability, quality, and cost. Retaining the example of the car, this means to redesign the vehicle, giving emphasis to the objectives of minimizing emissions by reducing weight and adopting an alternative propulsion system—hybrid, perhaps, or electric.

The third box, that of *industrial ecology*, derives from the perception of human activities as part of the global ecosystem. Here the idea is that the processes and balances that have evolved in nature might suggest ways to reconcile the imbalance between the industrial and the natural systems. The transport analog might be that of reexamining the concept of private transport, abandoning private ownership of vehicles and replacing it with a publicly owned system (driverless electric taxis, perhaps, charged from renewable-energy sources) that both fills the need and has minimal impact on the environment. The vision of a circular materials economy, described in a moment, fits into this box.

The last box, that of long-term *sustainable development*, requires thinking on a truly grand scale. Here is one (of many) formulation of what that will involve. How this will be achieved is not yet clear. For now we stay with a more achievable vision.

13.4 A circular materials economy²

Before the industrial revolution, materials were expensive and labor was cheap. The number of materials in service was small and their high value relative to labor ensured that the products made from them were maintained, repaired, and upgraded. Material efficiency was normal practice.

Since the industrial revolution, large-scale mining and global trade have allowed material costs to decline³ (look back at Fig. 12.2). At the same time labor costs have risen, causing manufacturing methods (mass production, robotic assembly, the Internet of things) to evolve to minimize its use. The availability and low cost of materials encouraged industry to adopt an increasingly open-loop approach to material resources, transforming them into products that are used once, then

²McDonough and Braungart (2002), “Cradle to cradle, remaking the way we make things,” North Point Press, New York.

³World Bank (2013), <http://blogs.worldbank.org/prospects/category/tags/historical-commodity-prices>.

discarded. Why conserve materials when they will be cheaper tomorrow than they are today? The flow of materials through the economy followed a linear path (Fig. 13.5).

Some 80% of material usage still follows such a path but there is an increasing awareness that this cannot go on. The global population is increasing. Three billion consumers from the developing world will enter the middle class by 2030,⁴ with associated demand for products and services. The global consumption of materials, at present about 77 billion tonnes per year, is expected to rise to 100 billion by 2030.⁵ The stress on the global ecosphere caused by industrial development already gives cause for concern. And—a more immediate driver—the cost of materials is now increasing considerably faster than that of labor (Fig. 12.2 again). An incentive is emerging to conserve materials rather than reject them. Increased material efficiency, reducing the resources per unit of manufacturing output, can make nonrenewable resources last longer, but their loss at the end of product life is a continuing drain. We examine ways to increase material efficiency in the next section, but first we explore the bigger picture: that of establishing a more circular materials economy.^{6,7}

Materials in a circular economy are seen, not as a disposable commodity, but as a valued asset to be tracked and conserved for reuse, in rather the same way that financial capital is invested, recovered as revenues, and reinvested. Fig. 13.6 introduces the idea. Materials are produced and manufactured into products that enter service, where they remain for their design life. In the circular model, disposal at end of life as landfill or waste is not an option. Instead the product is reused in a less demanding way, or reconditioned to give it a second lease of life, or dismantled

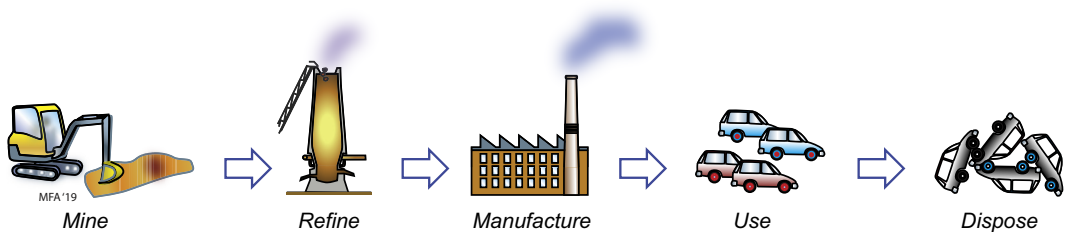


FIGURE 13.5 The linear materials economy: take—make—use—dispose.

⁴McKinsey Quarterly, February (2014), available from www.ellenmacarthurfoundation.org.

⁵<http://www.foe.co.uk/sites/default/files/downloads/overconsumption.pdf>.

⁶Ellen MacArthur Foundation (2014), www.ellenmacarthurfoundation.org.

⁷Webster, K., Bleriot, J., and Johnson, C., (2013), “A new dynamic: effective business in a circular economy.” Ellen MacArthur Foundation, UK.

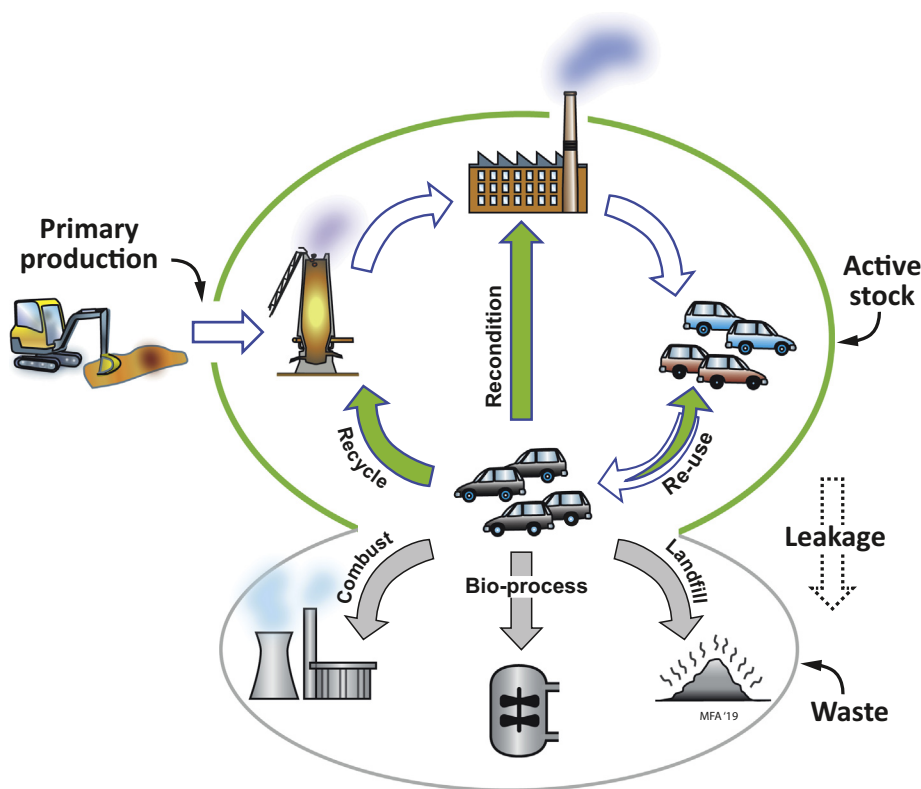


FIGURE 13.6 The circular materials economy. The aim is to retain materials in the “Active stock” balloon by reuse, reconditioning, and recycling, minimizing leakage into the Waste balloon.

into its component materials for recycling. All three of these options retain the materials of the product as *active stock* (the upper green ellipse in the figure). It may be impractical to recycle perishable materials; those that are bio-degradable can be composted, returning them to the biosphere; those that are combustible can be incinerated with energy recovery; only the remaining residue goes to landfill. The more material that can be retained within the green “Active stock” balloon (Fig. 13.6), the less needs to be added through primary production. Indeed, if better designs use materials more efficiently, it may be possible to function, at least for a while, with no primary production at all.

The circular economy means more than just efficient recycling. Taken literally, it means relying on renewable energy, tracking materials through the economy so that their location is known, and using them in designs that allow their reuse with as little reprocessing as possible. The concept goes beyond the mechanics of production and consumption of goods, moving from the idea of *consuming* materials to one of *using* them, somewhat in the way properly managed land is used for agriculture without consuming it.

That is the ideal. Ideals have value; they set a target, something to aspire to, even if perfect fulfillment is not possible.

Newsclip: “Business leaders in Davos keen to mainstream the circular economy.”

Chief executives said biggest barrier to progress is ingrained mind-set of ‘manufacture, use and dispose’.

The Guardian, April 30, 2014

13.5 Creating a more circular materials economy⁸

Material efficiency means providing more material services with less material production. Material *production* is not the same as material *consumption*. Material production measures the quantity of materials created per year from ores, feedstock, and energy. Material consumption measures the quantity of materials used in manufacture of all types per year. Consumption is greater than production because of the contributions of material recycling and reuse. Put another way, material efficiency means maintaining enough material in the Active stock balloon of Fig. 13.6 to provide the services we need while minimizing new material production flowing in from the left. Here we explore four broad strategies for achieving it:

- Better stuff: improved material technology
- Better design and longer product life
- Better business models
- Better behavior: regulation and change of lifestyle

13.5.1 Better stuff: improved materials technology. Improved material extraction and yield. Extracting and refining materials consumes 20% of global energy per year. Even an improvement of 1% in the efficiency of these processes would save much energy. New process routes offer potential for improved efficiency and greater yield. They’ll be needed: the ores we will mine in the future will be leaner than those we mine today.

New and improved materials. Material development, a century ago, was largely empirical. New materials emerged by trial and error and lucky accident. The rapid expansion of materials science in the second half of the 20th century

⁸The brief case studies illustrated in this chapter are drawn from a number of sources, among them: WRAP (2014), <http://www.wrap.org.uk/content/innovative-business-models-1#k>; Cradle to cradle case studies (2014), http://www.c2ccertified.org/innovation_hub/innovators; and the Ellen MacArthur Foundation (2014), http://www.ellenmacarthurfoundation.org/case_studies.

provided a more rational basis for material development, but material behavior is sufficiently complex that a component of inspired guessing and serendipitous discovery remained: an approach that has been described as “science-informed empiricism.” Today, the understanding of materials coupled with computational power has allowed *computational material design* to become a reality, opening a new era in material development.

13.5.2 Better design. Design for longer product life. One obvious way to reduce resource consumption is to extend product life. Doubling the life, you might think, halves material consumption. But durability has more than one meaning. A product reaches the end of its life when it is no longer valued. The cause of this rejection is, frequently, not the obvious one that the product just stopped working. As pointed out in Chapter 4, there are at least six end-of-life scenarios, ranging from physical breakdown to loss of desirability. Design to extend product life starts with an analysis of the life-limiting agency; there is little point in extending physical life (as an example) when the cause of rejection is outmoded functionality or change of fashion.

Most domestic appliances (refrigerators, washing machines, microwave and electric ovens) use much more energy during their life than it takes to make them in the first place. When this is so, extending product life may save materials but it does not always save energy. Advances in technology can reduce the use-energy; then making the product last longer can increase energy consumption. If the technology is advancing rapidly, early replacement can be more energy efficient than extension of life. And where is the incentive for a maker of products to extend life when a longer life means selling fewer products? The answer to that may lie in a product-service business model. We come to that in a moment.

Design for reuse, repair, and recycling. Value is added during the manufacture and assembly of a product; a brand-new family car, for example, is worth many times more than the steel, rubber, and glass of which it is made. After 10 years’ use the car has depreciated by a factor of 5 or more but some residual value remains. More value is lost if the car is broken down into components, and more still if it is shredded to allow its materials to be recycled. The sequence “reuse—repair—recycle” describes a descending path on the value chain: the first retains the most value, the last the least. But all three have the merit that the materials remain part of active stock.

Reuse. Products or their components can be taken back to be reused or restored for resale, a kind of nondestructive recycling. The user may change (1-year-old mobile phones are resold to those who cannot afford the newest model) and the function may change, too (old school buses are reused as camper vans, shipping containers are reused for housing), but their materials, once again, remain in active service. Well-established systems are in place to resell cars, boats, and houses for reuse when the first owner no longer wants them. For reuse to be a viable option there has to be a secure supply and consumers must trust it, needing quality assurance and price transparency. The success of eBay as an agent to enable reuse is a model for how this can be achieved.

Mazuma Mobile.

The average first life of a smartphone is 18 months, after which time it ends up in a drawer, hibernating. When the drawer fills up the phone goes to landfill. Mazuma targets these handsets early on to maximize their potential for reuse by reaching out to the customers directly, offering money in exchange.

“We try [...] to get the handsets as soon as someone upgrades so that we can maximize its use while it is still current,” says the CEO, Charlo Carabott. The challenge was to gain public awareness, which Mazuma tackled by investing in marketing and building trust. Most of the 100,000 phones it receives each month can be reused after minor refurbishing, handled by an external partner. Phones that do not work are recycled to recover materials.

Repair and remanufacture. Remanufacturing is the upgrading or renewal of an existing product. Extending product life by repair makes business sense where products are expensive and labor is cheap, but the business case for repair is weaker in developed economies, where the reverse is true. There are many successful examples: the reconditioning of car and truck engines, the reuse of modules in photocopiers, the reuse of printer cartridges, and the retreading of tires. Remanufacture works for products that are at the mature end of their development cycle, in a market in which technology change is slow.

Renault.

The circular economy framework emphasizes design for remanufacture rather than aiming solely to use less material. The Renault automotive company has embraced this interpretation. The company's plant in Choisy-le-Roi, near Paris, remanufactures automotive engines and other components for resale. Components are redesigned to make them easier to disassemble for closed-loop reuse, the old providing inputs for the new. Renault reports economic benefits, including tighter control of its raw materials throughout its vehicles' life cycles.

Caterpillar, Inc.

Some products fit a circular business model more easily than others. Machinery, engines, gearboxes, and drivetrains, particularly, lend themselves to reconditioning and remanufacture. Caterpillar is a US manufacturer of construction and mining equipment. The company runs “Cat Reman,” a remanufacturing program that returns products at the end of their lives to as-new condition and seeks new ways to reduce, reuse, recycle, and reclaim materials that once would have gone to landfill. The company estimates that 65% of their costs are material related, so salvaging components makes business sense.

Recycle. Recycling has one advantage over reuse: recycled materials reenter the primary production cycle and thus can be used in a greater number of ways, even though the loss of value is greater.

The key steps are separation and recognition. Airframe makers now stamp sheet metal with the alloy designation and polymer molders imprint moldings with designated recycle marks (Chapter 4). Recognition could be improved further by tagging components with bar codes or other identifiers that carry more detailed information, but none of these help if products are shredded before they are dismantled. To get further needs sophisticated, if unglamorous, materials science. When shredding is practiced, separation is possible by using the optical, magnetic, electrical, dielectric, or inertial signatures of the materials, but this is imperfect, able to distinguish material families but unable to separate individual grades. What is needed is an internal identifier, preprogrammed by the manufacturer, that can survive life and carry a designation tag to every shredded chip.

Ricoh.

Ricoh, a global maker of office machines, designs its GreenLine brand of office copiers and printers to maximize component reusability. Mixing new and reconditioned equipment enhances Ricoh's portfolio with lower-cost models, serves a wider range of customers, and generates additional revenue and margin by selling equipment more than once. Ricoh aims to reduce the input of new resources by 25% by 2020 and by 87.5% by 2050.

13.5.3 Better business models. Replacing products with services. Taxis are more intensively used than private cars. Laundromats are more intensively used than home washers. The replacement of goods by services increases use intensity (Fig. 13.7). This product-service model can also bring increased customer loyalty and reduced marketing costs. From a materials perspective, service design means that the ownership of products and their materials remains in the hands of the product maker. It is then in the interest of the maker to make the product last as long as possible and to allow reuse of its parts rather than scrapping them. This, in turn, drives design and material choice to increase life and durability. Product-service companies sell performance; it is not the product that carries the guarantee, it is the provision of the service. It is a small step from there to the idea of leasing the materials themselves, so that a manufacturer pays a rent for the time they are used but with the obligation to return them at the end of the rental period. Some materials are already treated in this way: uranium and thorium are examples.

	Car ownership replaced by mobility service (taxi, bus, train, Uber)
	Ownership of copier replaced by copying service (Xerox)
	Home washing machine replaced by clothes-washing service (laundromats)
	Ownership of truck tires replaced by tire service (Michelin)
	Ownership of aircraft engines replaced by “power by the hour” service (Rolls Royce)
	Smartphone replacing phone, watch, web-browser, television

FIGURE 13.7 *Examples of replacement of products by services.*

Digital Lumens.

Industrial lighting is inefficient and expensive. Warehouses, manufacturing, cold storage, and maintenance depots are in use 24/7, have high ceilings, and require continuous illumination. Digital Lumens offers intelligent lighting systems that combine LEDs, networking, sensors, and software to reduce lighting-related energy use by up to 90%. Digital Lumens offers their lighting product as a service rather than an equipment sale, reducing the up-front investment and making costs and benefits explicit.

Michelin.

Tire maker Michelin offers tire leasing programs with payment on a price-per-mile basis. The program offers reduced business risk, avoids variability in tire performance, and eliminates irregular purchase costs.

All this sounds good, but it is not so simple. Here (paraphrased) are revealing observations by the sustainability director of Interface,⁹ a carpet company.

⁹<http://greenallianceblog.org.uk/2011/09/29/can-services-replace-products-the-myths-and-truths/>.

A failed experiment.

Product-service systems look like a panacea for sustainability. At Interface we put effort into leasing carpet, but it didn't take off. Here's why.

A carpet is not the whole functional unit. When you lease a car, it includes the service, road tax, etc., so the client receives the full service and doesn't need to do anything but enjoy it. Leasing carpet is a bit like leasing a car wheel. You need the whole service, and in the case of carpet that is carpeted office space. There are already many people out there renting/leasing office space.

For a bank to finance a lease you need residual value. A £30k car after 3 years is still worth £10k–£15k. But carpet has negative residual value (cost of de-installation plus landfill or recycling). Which bank would be crazy enough to finance that?

Replacing materials with information. The applications on your computer probably cost more than the computer itself. The computer itself is made from materials, but with it you can communicate, write, draw, do research, buy things, and be entertained without using any material at all. At the commercial level information technology allows customized products to be made when ordered, removing the need to hold large stock. Similar dematerialization is spreading in retailing, manufacture, banking, education, and entertainment.

The “paperless office” may save materials but it still consumes resources. The digital economy (known as the ICT—the information—communications—technologies ecosystem) today consumes 2000 TWh (2×10^{12} kWh) per year, about 7% of the world's total electricity generation. Data centers serving Google, Facebook, Bitcoin, and the like are heavy energy users, currently consuming 1% of global electrical energy and responsible for 0.3% of global carbon emissions,¹⁰ levels expected to increase by a factor of 3 by 2030.

13.5.4 Better behavior: regulation, social adaptation, and change of lifestyle. Regulation. Governments have a broad range of economic instruments—carrots and sticks—to change the way we behave; we encountered some of them in Chapter 5. Such interventions may not be popular, but they can be effective. Most people would agree that reducing road deaths, improving public health, and creating a stable financial system are desirable goals. But it took legislation to enforce the wearing of seat belts and crash helmets, to ban smoking in

¹⁰Nature News Feature, “How to stop data centres from gobbling up the world's electricity,” September 13, 2018, <https://www.nature.com/articles/d41586-018-06610-y>.

public places, and to make High-Street banks back loans with adequate reserves. All three triggered opposition but, once in place, they achieved the desired outcomes and are now accepted. So regulation works. But, as mentioned earlier, regulation is also a wake-up call. It points to a design failure, something that better design could have made unnecessary in the first place.

Doing with less, doing without. Rich economies consume more resources than are necessary for an adequate standard of living. In developed countries cars, television sets, hi-fis, and iPods are seen not as luxuries but as necessities. Wealth in many communities is linked to status; possessions are wealth made visible. There is every reason to expect that, as the poorer but more populous countries become more affluent, they will take the same view. Breaking the link between status and possessions brings a decrease in material consumption. Some communities and religious orders have made this choice, electing to live without amassing more possessions than are necessary for life, but they are a tiny minority.

13.6 Getting real: how circular can we get?

What, exactly, does “a circular materials economy” mean? One view of a circular future is one in which waste no longer exists, where products are recycled indefinitely—an economy that perpetually gyrates without any input of depletable resources (an example is given by Cullen, 2017). Three obstacles make this an impossible dream: *stock dynamics*, *loss of quality*, and *loss of quantity* (Fig. 13.8).

Stock dynamics. Circularity means recovering the materials of a product at end of first life and reusing them to enable subsequent lives. Products take materials hostage, so to speak, locking them up for the duration of the product life. If demand for the materials has increased over the intervening time, even 100% recovery will not meet today’s demand (Fig. 13.9 and the following box). Take cars as examples:

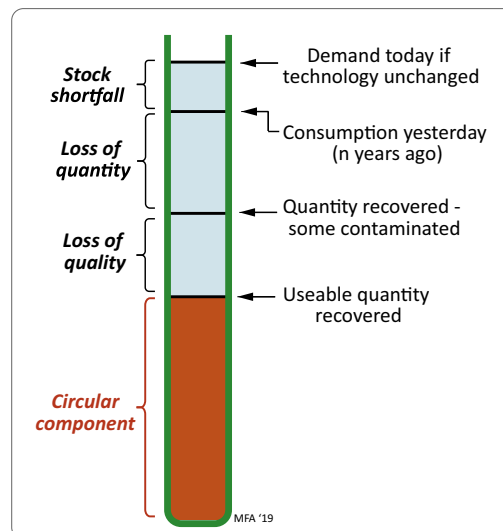


FIGURE 13.8 The ability of circularity to meet the today’s needs is limited by stock dynamics and loss of quantity and quality.

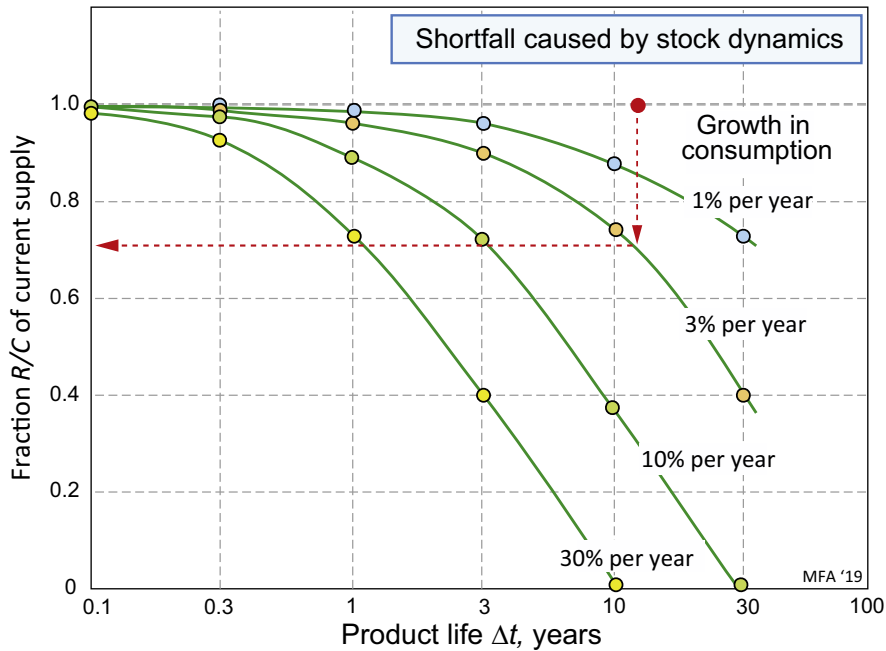


FIGURE 13.9 Stock dynamics. If consumption grows, recovery of material at end of life can meet only a fraction of today's needs.

the average life is 14 years, growth in consumption over the past 14 years was 3% per year (the red arrows on Fig. 13.9). The contribution of the materials of the cars of yesterday to today's demand, assuming 100% recovery, would be about 70%.

Modeling stock dynamics.

If consumption is growing, yesterday's stock, even with 100% recovery, will not meet the needs of today. If consumption yesterday was C_0 and has grown at r_c % per year, today's consumption is:

$$C = C_0 \exp\left(\frac{r_c}{100}\Delta t\right), \quad (13.1)$$

where Δt is the lifetime of the product. The quantity recovered at the end of life is:

$$R = fC_0, \quad (13.2)$$

where f is the fraction collected at end of life. The fractional contribution of yesterday's scrap to today's consumption is then:

$$\frac{R}{C} = \frac{f}{\exp\left(\frac{r_c}{100}\Delta t\right)}. \quad (13.3)$$

This is the expression used to construct Fig. 13.9.

Loss of quantity. One hundred percent recovery is economically unviable. Products, once sold, become dispersed, and within a product, materials are already dispersed. It is relatively easy to recover some of a material from some of the products, but finding it all is—to put it crudely—just not worth the effort. Think of recovering mobile phones at the end of first life. Some still work, and those that don't still contain components and materials with value. To recover them, the phones have to be collected. Some are easy to collect, but recovering every single one is unrealistic: the cost of the search would outweigh the gain. This trade-off can be modeled (see next box), with the result shown in Fig. 13.10. There is an up-front capital cost to set up the recovery system. It is defrayed as units are collected and their value is recovered. But the more that are recovered, the harder it is to find those that remain, driving up collection costs. Fig. 13.10 makes the point that 100% circularity is impractical; indeed the economically most attractive fraction—here around 79%—can be much less. High direct (labor) cost shifts the minimum in the curve to the left; high residual value of the product (or of its materials) shifts it to the right. Appropriate legislation (penalties for discarding, or financial incentives such as buyback) artificially shifts the minimum toward higher recovered fractions.

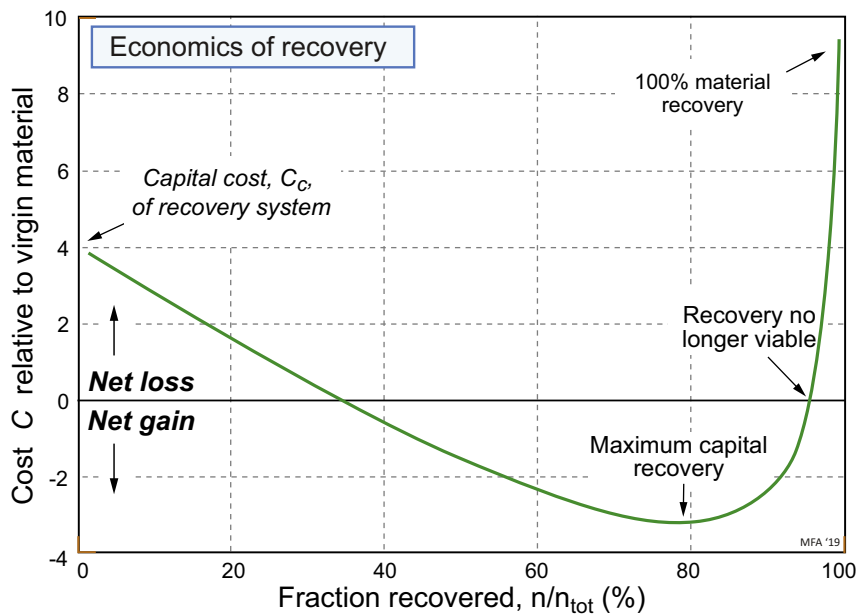


FIGURE 13.10 The relative cost of recovery depends on the fraction recovered. The economic sweet spot is at the minimum.

Modeling recovery cost.

Consider the broad economics of recovering units of a product to allow them to be reused, repaired, or recycled. The capital cost of the recovery system is C_c . The total number of units in circulation is n_{tot} . The number recovered at any point in time is n , so the recovered fraction is n/n_{tot} . The average value of a recovered unit is c_o . The value of the recovered fraction is then $n_{tot} c_o (n/n_{tot})$. The time t that it takes to recover a unit when n units have already been recovered increases because of the dispersion:

$$\frac{dn}{dt} = \frac{1}{t_o} (n_o - n), \quad (13.4)$$

where t_o is a constant. Integration gives the recovery time per unit, t_r , as a function of fraction recovered, n/n_{tot} :

$$t_r = n_{tot} t_o \ln \left\{ \frac{1 - 1/n_{tot}}{1 - n/n_{tot}} \right\}. \quad (13.5)$$

The direct cost of recovery is the recovery time t_r multiplied by the cost of time (labor, overheads, etc.), C_L . Summing the contributions gives the recovery cost C as a function of fraction recovered n/n_{tot} :

$$C = C_c - n_{tot} c_o \left(\frac{n}{n_{tot}} \right) + C_L n_{tot} t_o \ln \left\{ \frac{1 - 1/n_{tot}}{1 - n/n_{tot}} \right\}. \quad (13.6)$$

This is the function plotted in Fig. 13.10. The minimum occurs at the fraction:

$$\frac{n}{n_{tot}} = 1 - \frac{C_L t_o}{c_o}. \quad (13.7)$$

The model is overly simple, but it brings out important limits of collection economics: if none are collected, the cost is that of setup, C_c . As the fraction collected, n/n_{tot} , approaches 1, the collection cost tends to infinity. There is an optimal point in between.

Loss of quality. Loss of quality, too, limits circularity. It is impractical to recover manganese from automobile-grade steels (typically 1.2% Mn), but it is not necessary to do so; the steel can be recycled in the alloyed form. But this is not true of, say, germanium from end-of-life electronics; germanium in anything but pure form is worthless. Nonmetals, too, suffer from this problem, which constrains the recovery and reuse of most polymers and virtually all composites. When

virgin metals are alloyed, polymers are blended, or composites are mixed, there is an increase in entropy. Unmixing takes energy and energy means cost. Circularity is stifled when the marginal cost of the recovery of a material in useful form exceeds the marginal cost of the material in virgin form.

The red column in Fig. 13.8 is the fraction of today's need derived from recovery of yesterday's products after allowing for stock dynamics, loss of quantity, and loss of quality. The difference—the upper, blue part of the column—has to be met by draw-down of natural resources, the action we wish to avoid. Just how severely this constrains circularity today was illustrated by Fig. 6.16, which shows the actual contribution of recycled material to current supply. For some metals it is high: most of the lead and almost half of the steel and aluminum we use today have been used at least once before, but for most metals it is less. Among plastics, polyethylene terephthalate is the most significant success, with about 20% recovery, followed by polyethylene and polypropylene. The others are barely recovered at all.

13.6.1 A more inclusive view of circularity. The vision of a circular materials economy has appeal, suggesting future provision of material services without the troubling consequences of dwindling material resources, pollution, and waste. It is a vision with which governments and society at large have engaged, but it is one that can mislead. As we have just seen, a literal interpretation of circularity, one in which materials circulate endlessly, is totally unrealistic.

A more helpful interpretation is that of circularity as an attitude of mind rather than as a specific activity, one that conditions thinking about resource use in the widest sense and becomes part of the culture of an environmentally aware society. In this vein, Bolmsma and Brennan (2017) suggest thinking of circularity as an umbrella concept, one embracing and linking all activities that contribute to greater materials efficacy (Fig. 13.11).

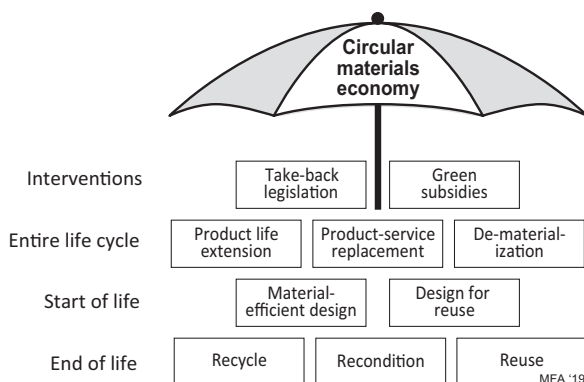


FIGURE 13.11 *Circularity as an umbrella concept, an attitude of mind rather than a single activity.*

13.7 Summary and conclusions

A linear industrial economy extracts natural resources, adds value by converting them into goods, distributes them, and then, at end of life, regurgitates them as waste. For most of the 19th and 20th centuries, the prices of resources have steadily decreased in real terms, providing little incentive to conserve them. Since the beginning of the 21st century, the trend has reversed; materials and energy have become steadily more expensive and increased demand from populous nations with rapidly growing economies has put stress on supply. A circular economy focuses not on acquiring resources but on conserving them by managing existing stock, maintaining it in active use and minimizing the “leakage” of stock to waste. There are many ways to do so, some within the remit of the materials scientist and engineer, some enabled by enlightened design to maximize useful life and ease reuse, others involving government incentives and controls, or requiring changed social perception and behavior. This chapter summarizes these and examines the challenges and opportunities they present.

A parallel is often drawn between natural ecology and industrial ecology, using the first as an exemplar of how the second might evolve into a balanced equilibrium with nature (Chapter 12). But are natural systems really at equilibrium? Over long periods of time, yes. The forces for change are minimal, allowing optimization by natural selection at an ever more refined and detailed level. It leads to an interdependence on a scale that even now we do not fully grasp, but which human-made activities too frequently disturb. But on a geological time scale there have been massive disruptions of the natural system arising, for instance, from sudden climate change. Are there lessons in the way the natural ecosystem has then adapted? When dinosaurs—reptiles—succumbed to one of these disruptions, some small, furry mammal—a mouse, perhaps—survived, evolved, and multiplied because it was better adapted to the changed climate and habitat. Where, in the technical world of today, are the postindustrial mice, and what do they look like?

We don’t know. But there is a message here. Survival lies in its diversity: new mice, ready and waiting. The nuclei of the new system existed within the old and could emerge and grow when circumstances changed. How do we create a society—a scientific and technological society—with sufficient diversity to ensure that the nuclei of the next phase preexist in it?

13.8. Further reading

- Allwood, J.M. and Cullen, J.M., (2012) “Sustainable materials: with both eyes open”, UIT Cambridge, UK. (*The authors present a carefully researched and documented case for increased material efficiency.*)
- Allwood, J.M., Ashby, M.F., Gutowski, T.G., and Worrell, E. (Editors), (2013) “Material efficiency: providing material services with less material production”, Phil Trans Royal Soc A, Vol. 371, Number 1986, Royal Society, London. (*The proceedings of a discussion meeting devoted to this topic.*)

- Ashby, M.F. (2016) "Materials and sustainable development", Butterworth Heinemann, Oxford.
- Azapagic, A., Perdan, S., and Clift, R. (Editors), (2004) "Sustainable development in practice", John Wiley, Chichester, UK.
- Blomsma, F. and Brennan, G. (2017) "The emergence of circular economy—a new framing around prolonging resource productivity", *Journal of Industrial Ecology* Vol 21 pp. 603–614.
- Braungart M. and McDonough, W. (2002) "Cradle to cradle: remaking the way we make things", North Point Press, New York.
- Coulter, S., Bras, B., and Foley, C., (1995) "A lexicon of green engineering terms", *Proc. ICED 95*, Prague, pp. 1–11. (*Coulter presents the nested-box analogy of green design, here used as Figure 13.4.*)
- Cullen, J.M. (2017) "Circular economy", *Journal of Industrial Ecology* Vol 12, No 3, 12599.
- Daly, H. (1990) "Toward some operational principles of sustainable development", *Ecological Economics*, vol. 2, pp. 1–6. (*Herman Daly, an economist at the University of Maryland, offers a simple set of operational principles to guide sustainable development.*)
- Ellen MacArthur Foundation (2014) www.ellenmacarthurfoundation.org. (*The Ellen MacArthur Foundation has become an enabler of thinking and communication on the circular economy.*)
- Ellen MacArthur Foundation (2017) <https://www.ellenmacarthurfoundation.org/programmes/insight/circularity-indicators>. (*Circularity metrics and tools to evaluate them.*)
- Geiser, K. (2001) "Materials matter: towards a sustainable materials policy", The MIT Press, Cambridge, MA. (*A monograph examining the historical and present-day actions and attitudes relating to material conservation, with informative discussion of renewable materials, material efficiency, and dematerialization.*)
- Guidice, F., La Rosa, G., and Risitano, A. (2006) "Product design for the environment – a life-cycle approach", Department of Industrial and Mechanical Engineering, University of Catania, Italy.
- Gutowski, T.G., Sahni, S., Boustani, A., and Graves, S.C. (2011) "Remanufacturing and energy savings", *Environmental Science and Technology*, America Chemical Society.
- MacKay, D.J.C. (2008) "Sustainable energy – without the hot air", UIT Press, Cambridge, UK and www.withouthotair.com/. (*MacKay brings a welcome dose of common sense into the discussion of energy sources and use. Fresh air replacing hot air.*)
- McDonough, W. and Braungart, M. (2002) "Cradle to cradle, remaking the way we make things", North Point Press, New York. (*The book that popularized thinking about a circular materials economy.*)

- Nguyen, Stuchtey, M. and Zils, M. (2014) "Remaking the industrial economy", McKinsey Quarterly, February issue. (*A readable introduction to the ideas behind a circular materials economy*) available on www.ellenmacarthurfoundation.org.
- USGS (2019), "Mineral commodity summaries 2018", U.S. Geological Survey. (*The ultimate source of data for mineral production and metal production.*)
- Webster, K., Bleriot, J., and Johnson, C. (2013) "A new dynamic: effective business in a circular economy", Ellen MacArthur Foundation, UK. (*A compilation of essays by distinguished authors discussing aspects of the Circular Economy.*)
- World Bank (2013) <http://blogs.worldbank.org/prospects/category/tags/historical-commodity-prices>.
- WRAP (2014) <http://www.wrap.org.uk/content/innovative-business-models-1#k>.

13.9 Exercises

E13.1. Distinguish *pollution control and prevention* from *design for the environment*. Use the example of dealing with an effluent-polluted beach to illustrate the difference between the two.

E13.2. What is meant by the *ecological metaphor*? What does it suggest about ways to use materials in a sustainable way?

E13.3. How does the Ellen MacArthur Foundation (a leading proponent of circular economics) define a circular materials economy?

E13.4. In what ways are natural ecosystems and modern technological systems different? Contrast the two, focusing on the elements on which they depend, their treatment of waste, and their metrics of well-being.

E13.5. How does a circular materials economy differ from the linear one largely practiced today? What motives lie behind each model? What view does each model take of the value of materials? Where does the ownership of the materials of a product lie in each model?

E13.6. The average life of a steel-frame bicycle Δt is 6 years, after which it is discarded, collected by the local council, and recycled. If a fraction $f = 0.8$ of discarded steel bikes is collected and, inspired by the Tour de France and environmental cycle ownership, is growing at $r_c = 8\%$ per year, what is the fractional contribution of discarded bikes to current production? Use Eq. (13.3) of the text to find out.

E13.7. Most newspapers are read on the day of purchase and then discarded. If the discarded paper is collected on a weekly basis and recycled after 10 days, the product life Δt is 17 days (0.047 years). If a fraction $f = 0.5$ is collected at end of life and newspaper readership is declining at $r_c = -4\%$ per

year as readers switch to tablets, what is the fractional contribution of discarded papers to current newspaper production? Use Eq. (13.3) of the text to find out.

E13.8. Electric vehicles (eVs) contain scarce elements. Many eVs are drive by DC motors containing neodymium–boron permanent magnets. Neodymium is a critical element (Table 12.1). If the magnets can be removed before the vehicle is shredded, the alloy can be reprocessed for the next generation of vehicles. The sales of eVs are currently growing at $r_c = 44\%$ per year, a rate expected to continue until 2030. The expected life of an eV is $\Delta t = 11$ years. If all the magnets in all end-of-life eVs could be collected (recycle fraction $f = 1$), what is the fractional contribution they would make to magnet production for future vehicles? Use Eq. (13.3) of the text to find out.

E13.9. An environmentally conscious city plans to set up a manned collection point for cast-off mobile phones. The direct costs (labor, heat, light, cost of space) are estimated to be $C_L = \$22$ per hour. The aim is to collect at least 10 phones per hour. The council plans to sell the phones on to recycling and reconditioning companies at an average bulk rate of $c_o = \$10$ per phone. The total number of units in circulation is n_{tot} . What recovered fraction n/n_{tot} should the council set as an optimal target? Use Eq. (13.7) of the text to find out.

E13.10. Exercise E13.8 concerned the recycling of magnets from eVs. It was assumed that the recycling rate for magnets from end-of-life eVs was 100%. Is this realistic? Suppose that the time to locate and extract a motor from an eV is $t_0 = 15$ minutes, direct costs are $C_L = \$30$ per hour, and the magnet material from one car has a value of $c_o = \$20$; what recovery fraction could reasonably be expected?

E13.11. Research the reuse of printer cartridges. Most printer makers have take-back schemes that provide useful information. What do they claim? What are the material savings? What are the economics?

E13.12. What happens to used smartphones? How circular is the life cycle of the average smartphone? Research this question and write a short report on your findings.

E13.13. Recycling is practiced today—most metals are recycled to some degree (up to 50%), as is paper and glass. The recycling of plastics is still much more limited (2%). Why is this difference so large?

E13.14. Is manufacture without waste possible? “Waste,” here, includes low-grade heat, emissions, and solid and liquid residues that cannot be put to a useful purpose. If waste is inevitable, why?

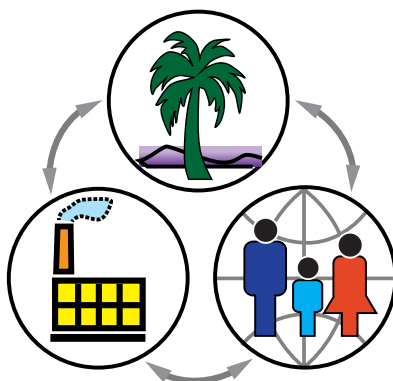
E13.15. What options are available for coping with the waste stream generated by modern industrial society?

E13.16. Recycling has the attraction of returning materials into the use stream. What are the obstacles to recycling?

E13.17. Car and truck tires create a major waste problem. Use the Internet to research on end-of-first-life tires. To what extent can tire lives be made circular?

E13.18. Packaging gets bad press. It does, however, perform a number of useful functions. Research the essential and the useful, if not essential, functions of packaging.

Materials and sustainability



14.1 Introduction and synopsis

What is “sustainable development”? In the words of the Brundtland Report,¹ it is “development that meets the needs of today without compromising the ability of future generations to meet their own needs.” This sounds right, but how is it to be achieved? And where do materials fit in?

Not everyone perceives sustainable development in the same way. An environmentalist might judge it by its contribution to the protection and nurture of the natural environment, preserving clean air, pure water, productive land, and a thriving biosystem. A humanist might instead look for its contribution to the generation and sharing of knowledge and understanding, and its respect for cultural values. The corporate view of sustainable development might accept these but see the financial health of the nation or corporation as the highest priority. Even the simplest of sustainable developments has environmental, economic, and social dimensions.

Recognition of this at the international level first appears in the Brundtland Report of the UN World Commission on Environment and Development in 1987 (Fig. 14.1). A series of initiatives since then has led to the wide-ranging

CONTENTS

14.1 Introduction and synopsis

14.2 Sustainable development and the three capitals

14.3 Assessing sustainable development at the national level

14.4 Assessing sustainable development at the product level

14.5 Corporate social responsibility and sustainability reporting

14.6 Resources, consumption, population, affluence, and impact

14.7 Summary and conclusions

14.8 Further reading

14.9 Appendix: Software to support social life-cycle assessment

14.10 Exercises

¹http://netzwerk-n.org/wp-content/uploads/2017/04/0_Brundtland_Report-1987-Our_Common_Future.pdf.



FIGURE 14.1 *The Brundtland Report 1987.*

interpretation of sustainable development formulated in the 2030 Agenda for Sustainable Development² adopted by all 193 member states of the United Nations in 2015. It defines 17 development goals that include ending poverty and

²The UN Sustainable Development Goals, [www.https://sustainabledevelopment.un.org/?menu=1300](https://sustainabledevelopment.un.org/?menu=1300).



FIGURE 14.2 The UN sustainable development goals for 2030.

inequality, improving health and education, stimulating economic growth, and tackling climate change³ (Fig. 14.2).⁴

Newsclip: “Business leaders join UN to rev up sustainable development investments.”

In a bid to scale up investment efforts to reach sustainable development targets, the Secretary-General on Wednesday convened the first meeting of a new UN-backed corporate alliance to discuss plans for spending on sustainability, likely to be in the trillions of dollars.

UN News, October 16, 2019

Newsclip: “World to miss UN sustainable development goals ‘by decades’.”

The world is decades behind schedule to meet the UN’s ambitious goals aimed at fighting poverty, hunger and climate change, experts have warned.

The Week, September 20, 2019

Adopting goals and achieving them are two rather different things.

³<https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019.pdf>.

⁴Image courtesy of <https://commons.wikimedia.org/w/index.php?curid=80531292>.

14.2 Sustainable development and the three capitals

The environment is a system (refer back to Fig. 13.1). The global financial and industrial complex is also a system. So, too, is human society. The three systems interact, weakly in some ways, strongly in others. When three already complex systems interact, the consequences can be hard to predict. When well managed, the systems can support sustainable development and globally rising standards of living. When less well managed, the interactions can lead to economic recessions and financial instability, loss of biodiversity and climate change, and social unrest and population migration. The 21st century has already seen them all.

Here is one view of sustainable development, one expressed in the language of accountancy: the triple bottom line or 3BL (Fig. 14.3, left side). The idea is that the balance sheet of a nation or a corporation should report not only the traditional financial bottom line (“profit”) but also its social/ethical (“people”) and environmental (“planet”) performance. In this view, sustainable practice requires that the bottom lines of all three columns show positive balances, represented by the “sustainable” sweet spot on Fig. 14.3. Many businesses now claim to implement 3BL reporting; indeed, the Dow Jones Sustainability Index⁵ of leading industries is based on it. But is it really possible for all three bottom lines to be positive at the same time? And do the terms “planet,” “profit,” and “people” really capture what we are trying to say?

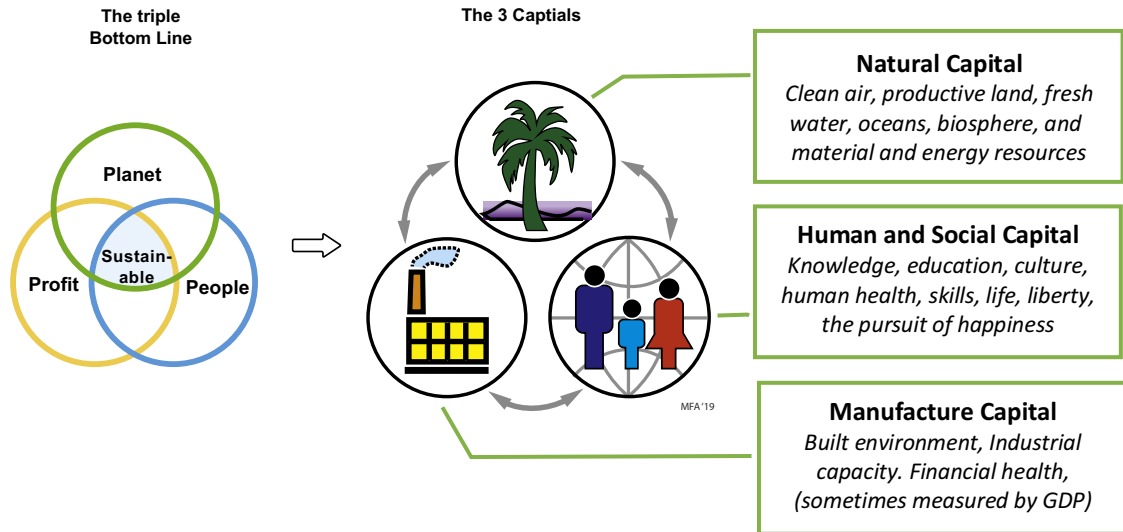


FIGURE 14.3 The “three P’s” and their reinterpretation as three “capitals.”

⁵Dow Jones Sustainability Index, https://en.wikipedia.org/wiki/Dow_Jones_Sustainability_Indices.

The three capitals. We make better progress if we separate the circles of the 3BL and unpack their content, so to speak. Here, a view of sustainability seen through the lens of economics can help. Global or national “wealth” can be seen as the sum of three components: the *net natural capital*, the *net manufactured capital*, and the *net human capital* (Fig. 14.3, right side). A capital is a finite asset that can be built up, conserved by appropriate husbandry, or drawn down and exchanged for other goods and services. The resources of the earth’s crust and oceans can be thought of as *natural capital*, an asset inherited from the planet’s geological and biological history. The accumulated infrastructure and wealth of a nation constitute its *manufactured and financial capital*, assets built up by investment and added value. Finally, the cultural and intellectual resources of a nation and the ability of its people to contribute to human welfare, development, and happiness can be thought of as *human and social capital*.

14.3 Assessing sustainable development at the national level

“If you can’t measure something, you can’t understand it. If you can’t understand it, you can’t control it. If you can’t control it, you can’t improve it.”⁶ That makes sense. What metrics have we got for the three capitals at the national level?



Natural capital. How do nations differ in the demands they make on natural capital? The *ecological footprint per capita*⁷ is an indicator of human pressure on the environment. It is a measure of the biologically productive land and marine area required to produce the resources and absorb the waste of a human population. It is reported in strange units: *global hectares (gha) per capita* (a hectare is 0.01 km²). The earth’s bio-capacity is estimated to be 2.1 gha per person—exceed that, and you’re living beyond your ecological means.

Fig. 14.4 plots the ecological footprints of nations. That of an average Canadian is 7 gha per capita, meaning that if the entire global population drew on resources at the same rate as a Canadian, it would require more than three earths to provide

⁶H. James Harrington, 2002, consultant and international performance improvement and quality guru.

⁷www.footprintnetwork.org; <http://data.footprintnetwork.org/#/abouttheData>.

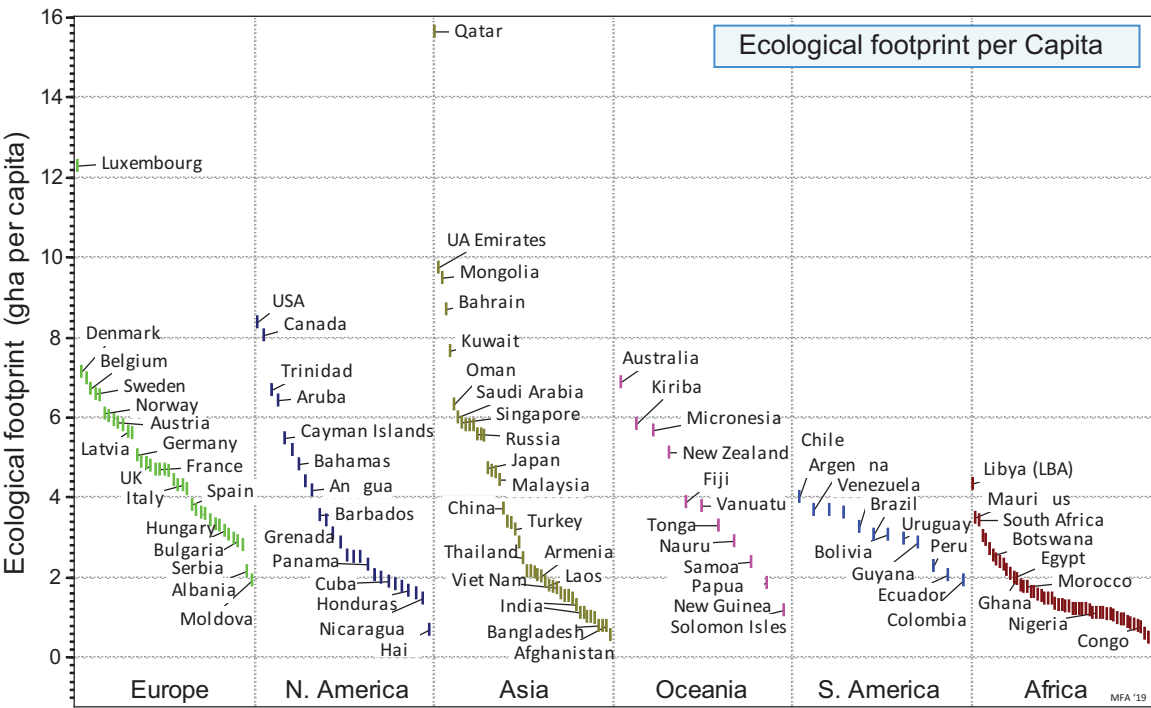
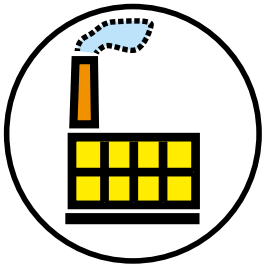


FIGURE 14.4 Ecological footprint of nations by region.

for them. Many African and Asian nations have ecological footprints well below 2.1 gha per capita. All the developed countries have ecological footprints that exceed that. If technological advances allow more productive use of land and improved recovery and conservation of nonrenewable resources, we could live on less. But it is worth remembering that population growth is exponential, technology progress is more nearly linear.



Manufactured and financial capital. Nations have departments of commerce to monitor national economic activity. There are several metrics for this, among them: gross domestic product (GDP), gross national product, and net national

income. We'll use the first of these. GDP is defined as "the value of all final goods and services produced in a country in 1 year." GDP per capita is often used as a metric for individual welfare. Countries with high GDP per capita are better able to afford investment in education, health care, social services, and the kind of research and development that produces new technologies. Its use as a measure of welfare does, however, have limitations: it ignores unpaid work (child care, for example), income from foreign aid, externalized costs (environmental damage in countries from which goods are imported), and the differences in hours worked per day in different countries to generate the same GDP.

With these limitations in mind, examine Fig. 14.5. Western Europe, the United States, Canada, the oil-rich states of the Middle East, and Australia all have high GDP per capita, well over \$30,000 per person per year, although the way wealth is distributed in some of these nations is very uneven. More than half of the nations of Africa have GDPs that are less than \$1000 per person per year, and here too the distribution can be skewed.

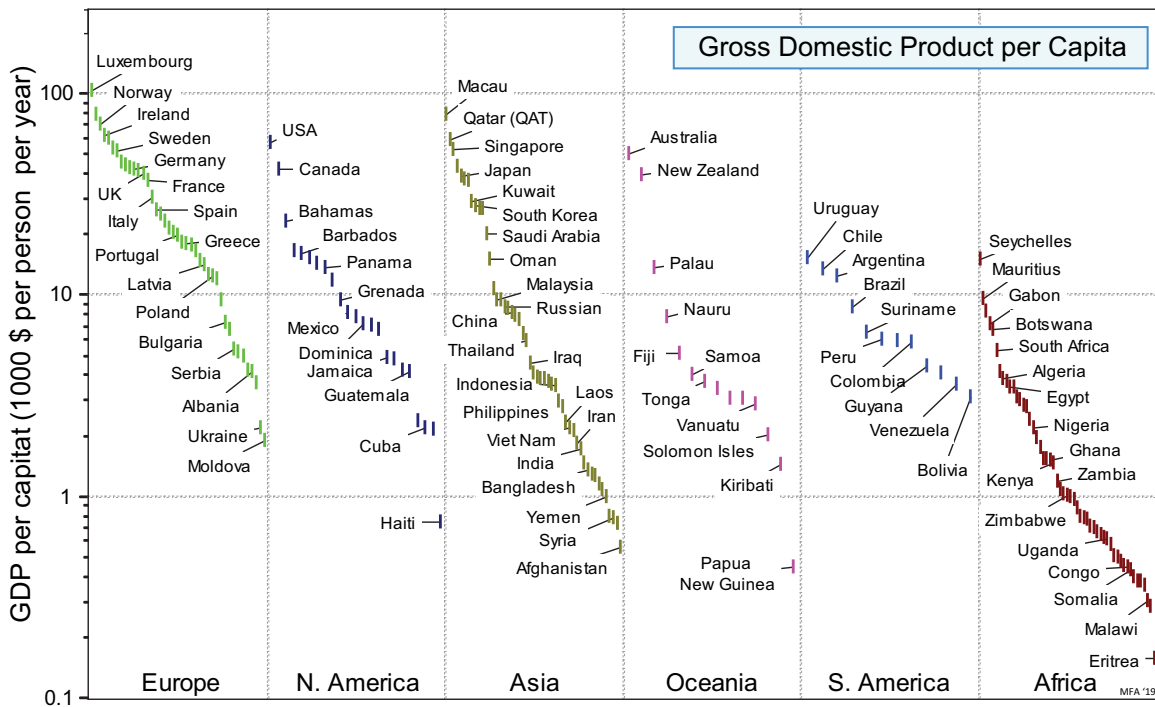
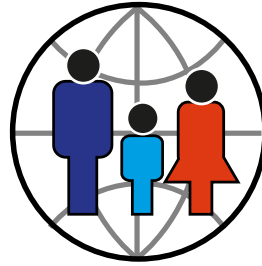


FIGURE 14.5 Gross domestic product per capita by region.



Social and human capital. Human welfare depends on more than economic growth. The *UN Human Development Index* (HDI)⁸ combines several welfare-related metrics to give a single ranking between 0 (undeveloped) and 100 (highly developed); they include expectancy of a long and healthy life, educational opportunity, and standard of living. It is a crude metric, capturing only part of what human development is about—it says nothing about inequalities, poverty, or the relative status of women in society, for instance, but it is a starting point.

Fig. 14.6 shows the UN HDI by region. A handful of countries, most of them in Europe and North America, have an HDI above 90. A much larger number, almost all in Africa, have an HDI below 60, even though many of them are resource rich. Wealthier but resource-poor nations see opportunities here and invest in production facilities to bring their natural resources to market, potentially boosting financial and manufactured capital in the producing country. But this translates into sustainable development only if coupled with improvements in the treatment of natural, social, and human capital.

Interdependence of the three capitals. The three capitals are not independent. Natural capital provides the materials and (at present) most of the energy that supports manufacturing and generates financial capital. These, in turn, provide the resources that support education, health care, and social support that are the building blocks of human and social capital. And it is the understanding and ability to reason engendered by human capital that provide the motivation to conserve natural capital. The three capitals have the potential to be mutually supportive.

They can also be mutually destructive. The consequences of profit-driven exploitation of nature without thought for the environmental or social disruption that this can cause are well documented. Nature can bite back: loss of habitat, biodiversity, and uplifting scenery detracts from the natural capital enjoyed by present generations and inherited by those of the future, undermining social and human capital.

⁸See <http://hdr.undp.org/en/>.

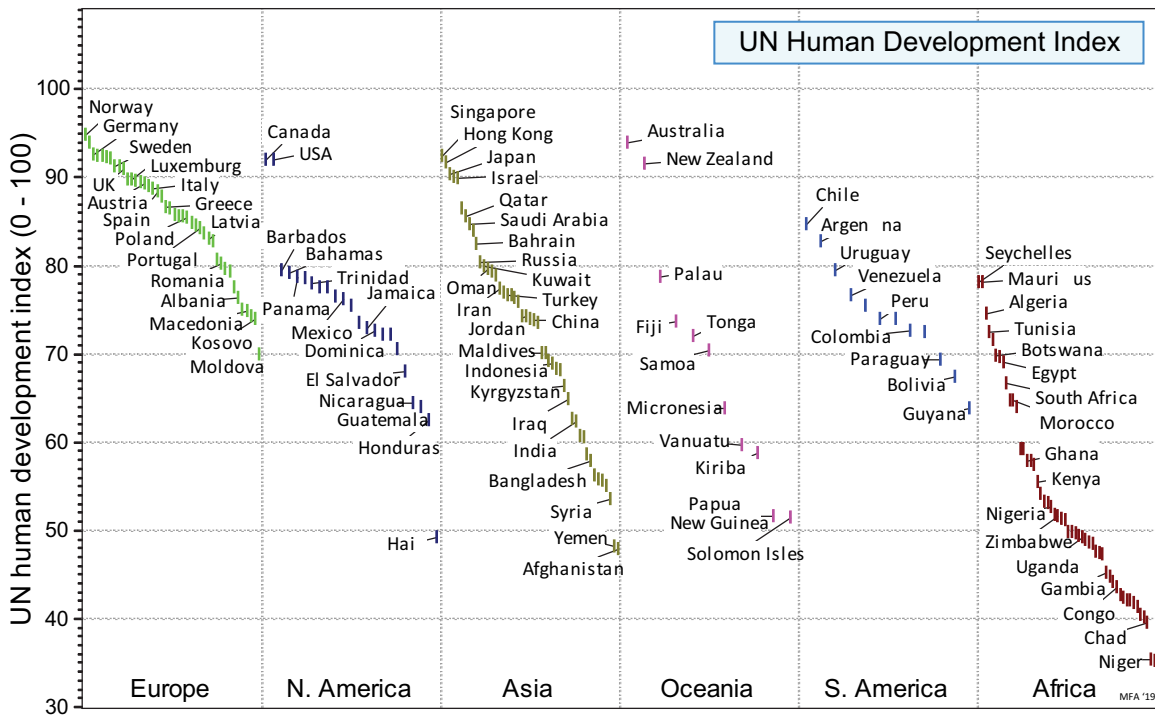


FIGURE 14.6 UN Human development Index by region.

Here are three (of many) examples of this interdependence.

Wealth and social security. Fig. 14.7 shows the national spend per person on social protection⁹ plotted against GDP per capita. On average, OECD (Organisation for Economic Co-operation and Development) countries spend 20% of their large GDP on benefits, health care, and pensions. Poorer nations spend as little as 1% of a far smaller GDP on the same services. Financial capital enables social care.

Wealth and commitment to the common good. The Good Country Index¹⁰ is a compound of UN, World Bank, and other nongovernmental organization

⁹**Social protection spend** includes child and family benefits; benefits for unemployment, sickness, employment injury, maternity, and disability; and old age pensions, <http://www.social-protection.org/gimi/gess/ShowWiki.action?id=594#tabs-3>.

¹⁰**The Good Country Index** is a measure of a country's contribution to the common good of humanity. It is based on data from the UN and other international organizations, measuring contributions to "science and technology," "culture," "international peace and security," "world order," "planet and climate," "prosperity and equality," and "health and well-being" <https://www.goodcountry.org/index/results>.

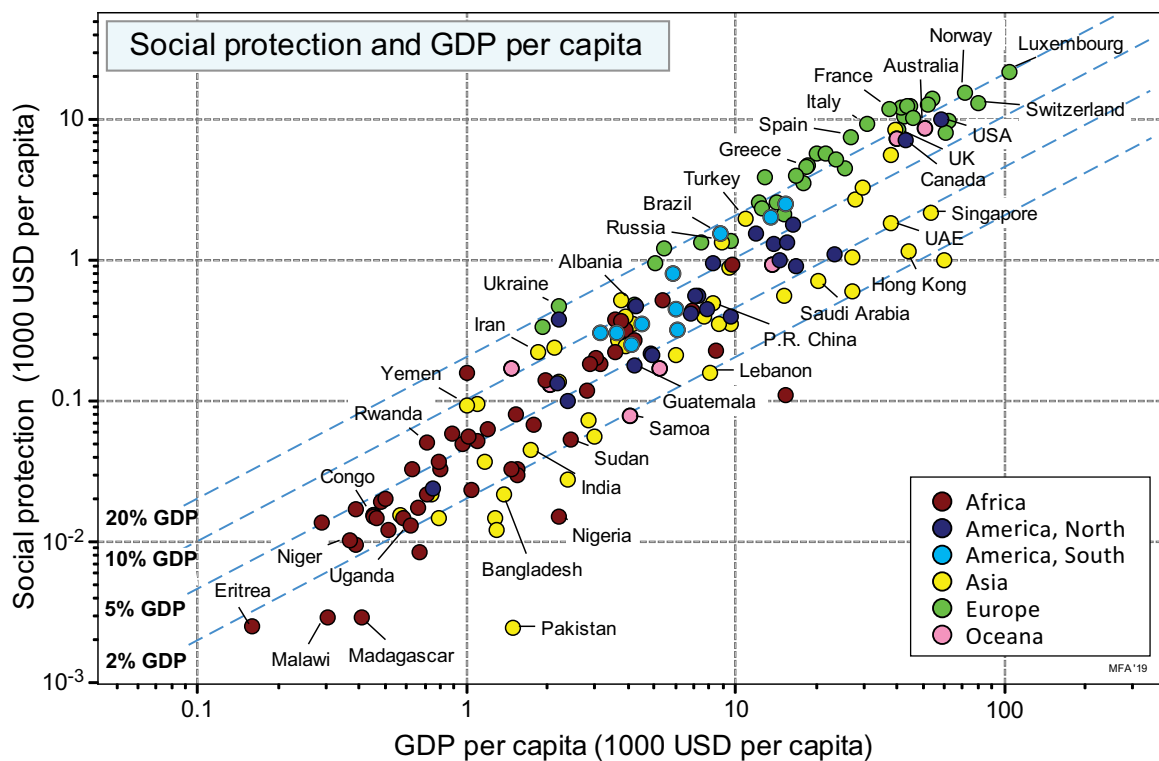


FIGURE 14.7 *The social protection provided by nations and their gross domestic product (GDP) per capita.*

(NGO)-researched data cataloging the quality of life of the population of a given nation and the contribution that nation makes to global welfare and peace. Here (Fig. 14.8) it is plotted against GDP. The scatter is greater than in the previous plot, meaning that GDP is not the only variable involved, but it is clear that greater disposable income provides an opportunity for greater altruism.

Figs. 14.7 and 14.8 suggest that prosperity increases human welfare. As the nations with low GDP per capita (Fig. 14.5) become wealthier, their quality of life can evolve in a socially positive way. The economic history of China since 2000 supports this view, one that is consistent with at least three of the UN's sustainable development goals of Fig. 14.2. But it brings with it a correlation of a more troubling kind, illustrated next.

Wealth and the environment. Globally, affluence is increasing. Increased affluence, if shared and appropriately invested, has the potential to increase human and manufactured capital. Fig. 14.9, however, illustrates that it increases

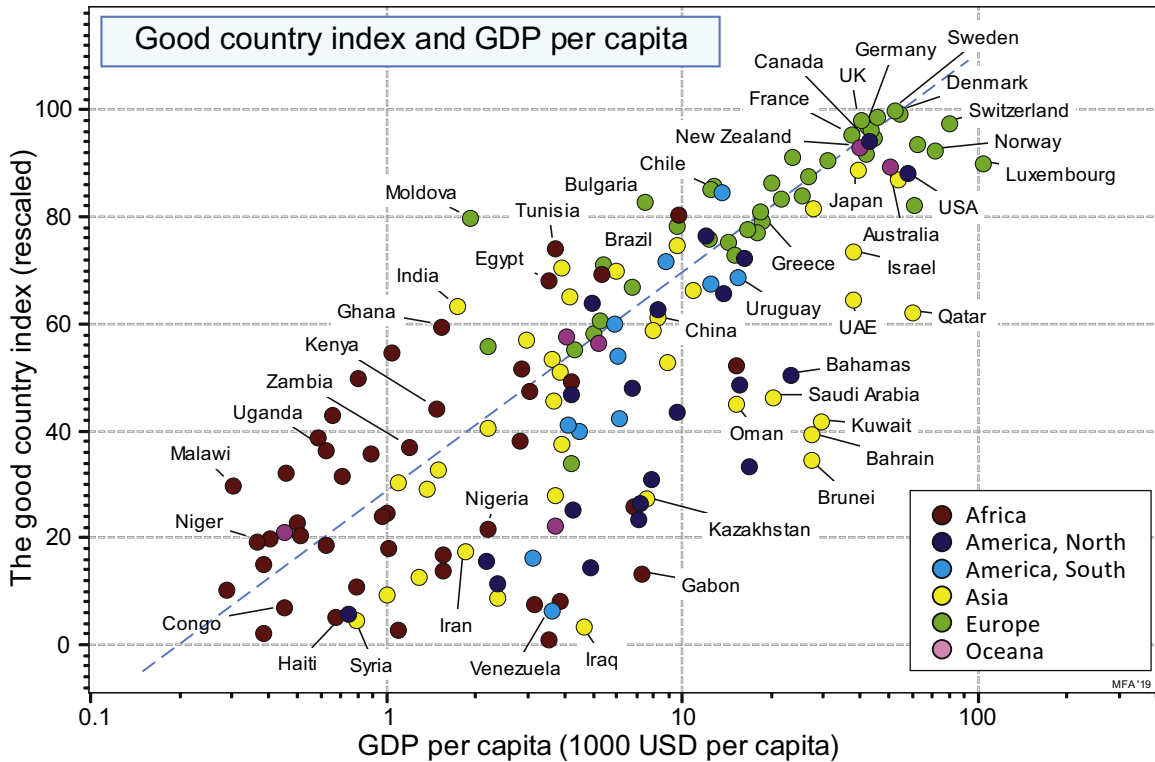


FIGURE 14.8 *The Good Country Index (rescaled 1–100) and gross domestic product (GDP) per capita.*

the drain on natural capital. The figure documents how the ecological footprint of a nation increases with its GDP. The greater the wealth of a nation, the greater is the productive land area required to support its population.¹¹

There are many other ways in which the three capitals influence one another. Any case supporting sustainable development should include an analysis of all three and the ways they interact.

14.4 Assessing sustainable development at the product level

The strategic planning of many materials-intensive enterprises had, in the past, prioritized the financial returns to their owners and shareholders. Narrow focus on financial return alone may bring success in the short term. But there is now

¹¹Very approximately, the ecological footprint is proportional to the square root of GDP.

Section 14.6 digs deeper.

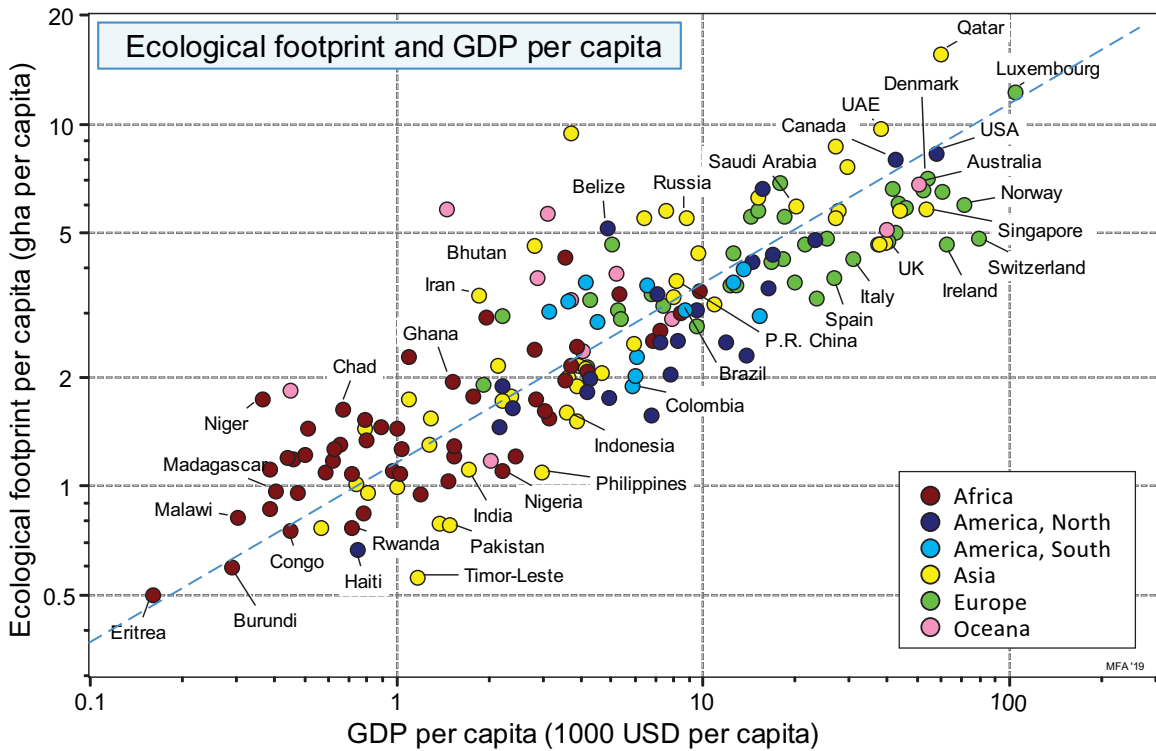


FIGURE 14.9 *The ecological footprint of nations and their gross domestic product (GDP) per capita.*

an awareness that the longer-term success of a company is measured not only in financial terms but also in terms of stewardship of the environmental and human resources on which the company draws, the welfare of its employees, and the health of the local economy of the regions in which the company does business.

It should be remembered that companies are not people. The primary responsibility of a public company remains that of maximizing return to shareholders while acting within the law—but this is not incompatible with the broader view just described. Increasingly, corporations and companies see their social and environmental responsibilities not as “optional extras” but as business imperatives able to create competitive advantage and build respect, trust, and loyalty.

Tools have evolved to assess the impact of product development on the three capitals.

14.4.1 *Natural capital: environmental life-cycle assessment.*

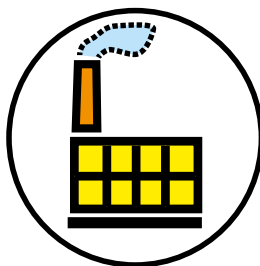


We met environmental life-cycle assessment (E-LCA)¹² and its ultimate metric—the health of the environment—in Chapter 3. The Society of Environmental Toxicology and Chemistry (SETAC) guidelines of 1991, subsequently absorbed into the ISO 14040 set of standards, define the steps for carrying out an E-LCA:

- *Set the goals and scope:* Why do the assessment? What is the product or service and which parts of its life are assessed?
- *Inventory compilation:* What resources are consumed? What emissions are released?
- *Impact assessment:* What do the resource consumption and emissions do to the environment—particularly, what bad things?
- *Interpretation:* What do the results mean? If bad, what can be done about it?

Conducting an E-LCA that meets the ISO standards is a skilled job, requiring expert assessors and independent verification. Services and specialized software exist to provide these, but they are slow and expensive. As explained in Chapter 3, “streamlined” methods have evolved to allow a quicker, approximate assessment. These are not substitutes for a full E-LCA when a definitive assessment of a product is sought. Their value is their ability to flag potential “ecological hot spots”: aspects of product life that may, potentially, be damaging to the environment or that might prompt a designer to make changes that improve eco-performance.

14.4.2 *Manufactured and financial capital: life-cycle costing.*



¹²ISO 14004–14044 (1990–2006), “Environmental management—Lifecycle assessment—Requirements and Guidelines,” International Organization for Standardization.

Companies have accountants to document their income, outgo, liabilities, and profits. As already mentioned, the first responsibility of a company is to its shareholders; a trading profit allows them to be rewarded for their investment. It also allows the company to expand and—if the directors so decide—invest in lower-carbon technology, material-efficient design, and improved conditions for its workforce. If the brand image so created increases share value, investors are further rewarded.

14.4.2.1 Human and social capital: social life-cycle assessment. Products provide functional utility: shelter, transport, and protection, for example. They also carry social utility: prestige, status, convenience, cultural associations, and pleasure. Product life can also harm human well-being through unfair employment practices, poor working conditions, regional exploitation, and failure to respect human rights.

Social life-cycle assessment (S-LCA) is about the behavior of the enterprises making the product and the social and political norms of the nations in which it takes place. Methods for conducting an S-LCA have their origins in the UN Environment Programme (UNEP)/SETAC “Guidelines for Social Life Cycle Assessment of Products”¹³ of 2009 (Fig. 14.10). It draws on the same underlying methodology as that of an E-LCA, with the focus now on the impact of product life on the well-being of the stakeholders. To understand how an S-LCA works, we need a closer look, following the same steps as for an E-LCA.

S-LCA goals and scope. The ultimate goal of an S-LCA is to improve social conditions and the socioeconomic performance associated with a product throughout its life cycle. The scope is set by the stakeholders. The UNEP guidelines identify five stakeholder groups:

- *workers* directly involved in any aspect of the life of the product;
- *consumers* who use it and, often, dispose of it at end of life;
- the *local community* directly involved with these actions;
- the surrounding *society*, providing the stage for these actions; and
- what you might call “*any other interested party*”—shareholders, NGOs, or the state, for instance.

¹³UNEP (UN Environment Programme)/SETAC (2009), “Guidelines for Social Life Cycle Assessment of Products” (http://www.unep.fr/shared/publications/pdf/dtix1164xpa-guidelines_slca.pdf) and Methodological Sheets for Subcategories (https://www.lifecycleanitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf). These are under review as of this writing, with a new release planned for 2021.

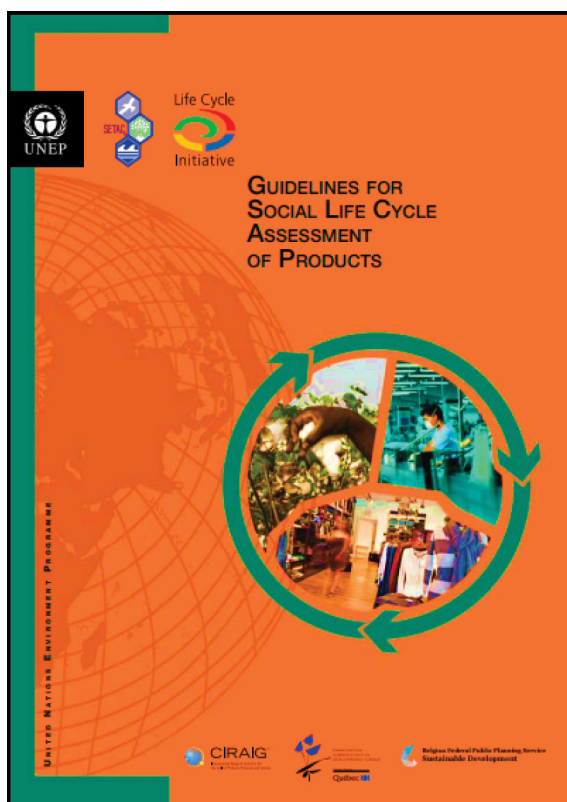


FIGURE 14.10 *The UN Environment Programme/Society of Environmental Toxicology and Chemistry report.*

S-LCA inventory compilation: social impact categories. A social impact is one that alters the way people live, work, relax, and relate to one another. The UNEP guidelines suggest 31 impact categories broadly relating to:

- human rights and equity
- health and safety
- working conditions and fair pay
- freedom of speech and association
- social support and welfare
- good governance and control of corruption
- human well-being in the broadest sense

The social impact inventory itemizes how stakeholders are affected (or might be affected) by the sourcing of materials for the product, its manufacture, its use, and its disposal. Nations differ in the norms, standards, and respect that they

commonly apply in dealing with social impacts, so the geographical location in which each of these phases of life takes place is an important input in making the inventory.

S-LCA impact assessment. The interactions identified in the inventory step can have both positive and negative consequences. The aim of impact assessment is to identify social hot spots—points of contact between stakeholders and aspects of the manufacture, distribution, and use of the product that may, potentially, be damaging or could be influenced in a positive way.

S-LCA interpretation and options for action means seeking patterns in the distribution of hot spots across product life and stakeholder groups, prioritizing options for action, and making recommendations that reduce social friction or inequity and enable constructive change.

How is an S-LCA used in practice? Proponents see it as contributing to the following activities:

- providing an overview for due diligence in setting up supply chains or manufacturing routes;
- informing decision-making in product development and establishing material supply chains;
- understanding the social aspects of material choice;
- funneling social investment in community projects;
- comparison of different options for products and services;
- comparison and benchmarking of suppliers;
- as a basis for certification and labeling;
- marketing and communication;
- as input to corporate sustainability reporting (introduced in Section 14.5).

14.5 Corporate social responsibility and sustainability reporting¹⁴

Corporate social responsibility. The concept of *corporate social responsibility* expresses the expectations that companies have moral, ethical, and philanthropic responsibilities in addition to their responsibilities to earn a fair return for investors and to comply with the law. More specifically, the expectations are as follows:

- *Economic:* Corporations will act with the shareholder interests in mind.
- *Legal:* Corporations will comply with the laws that govern competition in the market, including consumer protection and product laws, environmental laws, and employment laws.

¹⁴A good review of corporate social responsibility is given at www.referenceforbusiness.com/management/Comp-De/Corporate-Social-Responsibility.html.

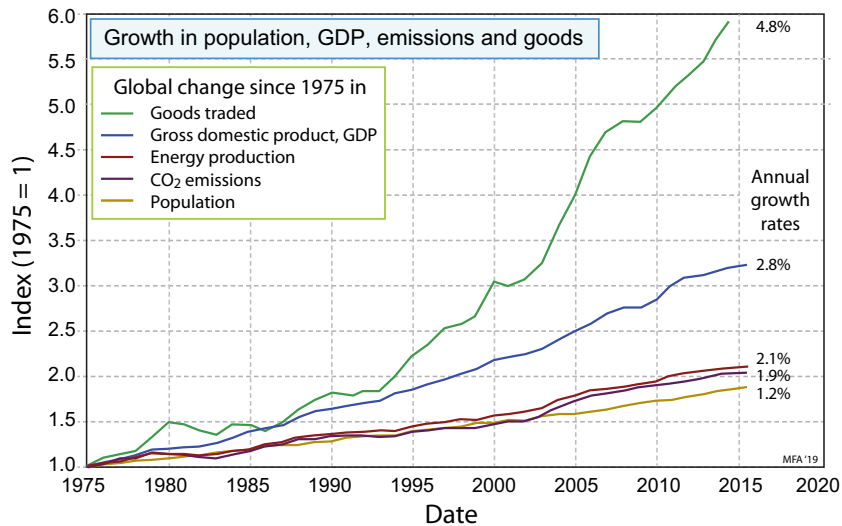


FIGURE 14.11 Growth of global trade in goods, gross domestic product, energy use, CO₂ emissions, and global population, 1975–2016 (World Bank Development Indicators (2017)).

- **Ethical:** Corporations will meet societal expectations that go beyond the law by conducting their affairs in a fair and just way.
- **Discretionary:** Corporations will meet society's expectation to act as good citizens via philanthropic support of programs benefiting a community or donating employee expertise, time, and financial support to worthy causes.

Sustainability reporting. Today, companies publish the economic, environmental, and social aspects of what they do in *sustainability reports* (SRs). The practice started in the 1980s as a way of countering the negative image that some chemical and mining companies had acquired by their treatment of the environment and of the local communities in which they operated. If done responsibly, an SR can enhance brand image and company reputation. It helps set new goals and increases transparency, catalyzing change within the company. But it can also be misused to suggest that a company has an environmental and ethical agenda when in reality little is done—a practice known as “greenwashing.”

Sustainability reporting is now widely practiced and has been mandatory in the European Union¹⁵ and the United States¹⁶ since 2018. The Global Reporting Initiative¹⁷ (GRI) provides a framework for doing this, based on the 10 principles of the UN Global Compact,¹⁸ listed in the box at the end of this section. Participants commit to the principles and to publishing an annual report covering three now-familiar categories:

- **Economic:** Financial results, market presence, and procurement practice
- **Environmental:** Use of materials, water, and energy; emissions; and compliance with environmental legislation
- **Social:** Labor practice, human rights, society, product responsibility

Some 80% of companies now do so.

Company performance in sustainability reporting is monitored by independent organizations that award “sustainability index” rankings. They are influential; investors use them as a guide for environmentally and socially responsible investment. Here are two:

- **The FTSE4Good Index¹⁹** claims to be an objective measure of the performance of companies in meeting globally recognized corporate responsibility standards.
- **The Dow Jones Sustainability World Index²⁰** identifies global sustainability leaders through their corporate sustainability reporting, focusing on their strategies for climate change, energy consumption, human resources development, knowledge management, stakeholder relations, and corporate governance.

¹⁵https://ec.europa.eu/info/business-economy-euro/company-reporting-and-auditing/company-reporting/non-financial-reporting_en.

¹⁶<https://corpgov.law.harvard.edu/2018/12/03/state-of-integrated-and-sustainability-reporting-2018/>.

¹⁷<http://www.globalreporting.org>.

¹⁸<https://www.unglobalcompact.org/what-is-gc/mission/principles>.

¹⁹<https://www.ftserussell.com/products/indices/ftse4good>.

²⁰<https://eu.spindices.com/indices/equity/dow-jones-sustainability-world-index>.

UN Global Compact—The Ten Principles

Human rights—Businesses should:

1. support internationally proclaimed human rights
2. avoid complicity in human rights abuses

Labor—Businesses should:

3. uphold the freedom of the right to collective bargaining
4. eliminate the use of forced and compulsory labor
5. eliminate the use of child labor
6. eliminate discrimination in hiring and promotion

Environment—Businesses should:

7. support a precautionary approach to environmental challenges
8. adopt initiatives to promote environmental responsibility
9. develop and use environmentally friendly technologies

Anticorruption—Businesses should:

10. work against corruption in all its forms
-

Case Study: A Sustainability Report

Anglo American²¹ is a large mining company with operations in North and South America, Africa, and Australia producing iron, copper, manganese, nickel, platinum, and diamonds. Mining, in the past, has incurred a negative image of exploitation and environmental negligence. Anglo American has issued annual SRs since 2000 following the guidelines of the GRI, described earlier.

Some background will help. The mining business, like the oil business, has certain special characteristics:

- It involves large-scale projects that require large investments over long time periods.
- The mines are sometimes in remote, environmentally sensitive, and technically demanding locations, in countries with uncertain political and regulatory management.
- The resources themselves belong to sovereign states; the company's license to operate is based on mutual benefit.
- Mining operations have significant environmental impact that may affect resources used by local and indigenous communities.

- Mining companies employ local people but also attract workers from elsewhere. This can create tensions among stakeholders, potentially jeopardizing the company's social license to operate.

Anglo American's 2018 SR states the intent to “re-imagine mining to improve people's lives,” combining “integrity, creativity and smart innovation, with the utmost consideration for our people, their families, local communities, our customers and the world at large.” The company sees its responsibilities as extending from the earliest stages of exploration to well beyond the life of the mine itself. The report includes Excel spreadsheets reporting mine production, energy and water use, environmental metrics, and human resource management over time, allowing progress to be monitored.

The report is independently validated by PricewaterhouseCoopers. Anglo American is listed in the FTSE54Good ethical index.

²¹ <https://www.angloamerican.com/sustainability>.

14.6 Resources, consumption, population, affluence, and impact

The planet's population, now over 7 billion, is continuing to grow. This growth, by itself, is a cause for concern—we already consume resources at a faster rate than nature can replace them. Seeing this simply in terms of population, however, is to underestimate the problem. Since the 1980s, global trade, GDPs, energy consumption, and carbon emissions have all grown faster than the population (Fig. 14.11). People are not only getting more numerous; they are also becoming more affluent.

The *IPAT* equation²² is an attempt to describe how growing population, affluence, and technology affect the environment. It makes the assumption that human impact (*I*) on the environment equals the product of population (*P*), affluence (*A*), and technology (*T*):

$$I = P \times A \times T \quad (14.1)$$

Here, *P* is the population of a region—it could be a single nation or it could be the whole world. Affluence, *A*, describes the spending power and, with it, the resource consumption and emissions of an average member of the population; we're using GDP per capita for this. The variable *T* is the resource intensity of the production of affluence, that is, the resources consumed in creating,

²² Much more can be said about the IPAT equation. For a fuller discussion see https://notendur.hi.is/~bdavids/UAU_102/Readings/Chertow.pdf.

transporting, using, and disposing of the goods and services that create one unit of GDP. Improvements in efficiency can reduce resource intensity, reducing T . Technology can affect environmental impact in more than one way, so the unit for T depends on what is being studied: if climate change is the subject, the unit is greenhouse gas emissions per unit of GDP.

Differentiating the IPAT equation we find:

$$\frac{dI}{I} = \left(\frac{dP}{P}\right)_{A,T} + \left(\frac{dA}{A}\right)_{P,T} + \left(\frac{dT}{T}\right)_{P,A} \quad (14.2)$$

The global population P is growing at 1.3% per year, and the growth of affluence A , measured by the global GDP, has averaged 3% per year since 2010, so for impact I to remain static, technology T must bring an annual decrease of 4.3% in resource intensity per year.

Example: Uganda is one of the world's faster-growing nations. Its population (2018 data) is growing at 3.3% per year and its GDP is growing at over 3.4% per year. Assuming that population P , affluence A (measured by GDP), and technology T are mutually independent, technological improvement to avoid an increasing impact on its natural resources requires an increase in resource-use efficiency of $3.3\% + 3.4\% = 6.7\%$ per year.

The IPAT equation gives qualitative insight, but to make it quantitative it has to be refined. The parameters P , A , and T are not independent (as Eq. 14.2 assumes). As an example, rising affluence slows population growth; wealthy people have fewer children. As a second example, doubling technological efficiency T should halve environmental impact I , but this does not happen because efficiency drives down prices, stimulating additional consumption, a phenomenon known as the *rebound effect*.

What magnitude of technical advance T is realistically possible? The EU legislation for fleet-average carbon emissions mandates a 25% reduction by 2020 relative to the value in 2015. That translates into a requirement for T of -4.8% per year, perhaps possible with a shift from internal combustion to electric propulsion. In 2016–2017, carbon emissions per kilowatt of electrical power generation in the United Kingdom fell by 3% as increased wind and solar generating capacity came online. Domestic electric power consumption fell by 1.6% per year between 2010 and 2018, largely as a result of installation of LED lighting. These three sectors have seen major technical innovations (hybrid and electric vehicle technology, wind power, LED sources). Other significant sectors (manufacture, domestic heating) have seen advances too, but achieving values of T above 5% per year in any of them seems out of reach.

14.7 Summary and conclusions

The Western view of development is one of economic growth based on urbanization and technical innovation, using global markets to source resources and to distribute goods and services. The economic histories of developed nations suggest a natural progression from early agrarian society through industrialization to a postindustrial economy in which wealth increases faster than population, thereby enabling further economic growth, and with it a more affluent society. In this view less developed nations should emulate the Western model, opening their countries to Western values and to global trade in resources, goods, and services.

The concept of *sustainable* development challenges this technocentric view. There is a growing recognition that it is simply not possible for all nations to replicate the lifestyle of the West—the planet's atmosphere is not able to absorb the resulting emissions, its natural hydrological cycle cannot provide the necessary fresh water, and the present-day international scramble to secure access to mineral resources suggests that these, too, are under pressure.

We are in an exceptional period. Global population is increasing—it has done that throughout most of the world's history. But affluence is also increasing, particularly in the world's most populous nations, and at a faster rate than at any time in history. The combination is putting natural resources, national economies, the environment, and social structures under unprecedented pressure. Technology can (as it has in the past) do something to compensate, but the numbers suggest that the increased demand may outstrip the efficiency gains that technical advance can deliver. Adapting our collective behavior to deal with these pressures is at the core of sustainable development.

Sustainable development, at the time of writing, is a vision, a grand ideal. Ideals have value; they set a target, something to be worked toward even if perfect fulfillment is not possible.

14.8 Further reading

- Azapagic, A., Perdan, S., and Clift, R. (Editors), (2004) "Sustainable development in practice", John Wiley, Chichester, UK.
- Baker, S., (2013) "Sustainable development", Routledge, New York. (*A concise and readable explanation of sustainable development taking a global and national perspective.*)
- Carson, Rachel (1962) "Silent Spring" first published by Houghton Mifflin, republished (2002) by Mariner Books. (*The book, which argued that the uncontrolled use of pesticides was harming birds and animals, including humans, had an enormous impact.*)
- Daly, H., (1990) "Toward some operational principles of sustainable development", *Ecological Economics*, vol. 2, pp. 1–6. (*Herman Daly, and economist at the University of Maryland, offers a simple set of operational principles to guide sustainable development.*)

- Dasgupta, P., (2010) "Nature's role in sustaining economic development", Phil. Trans. Roy. Soc. B, vol 365, pp. 5–11. (*Dasgupta argues that measuring well-being by GDP, education, and health ignores the loss of natural capital through damage to the ecosystem.*)
- Ehrenfeld, J.R., (2008) "Sustainability by design", Yale University Press, New Haven, CT. (*John Ehrenfeld is both a scientist—an industrial ecologist—an philosopher. The book is an interesting blend.*)
- European Union Eurostat, (2013) <http://epp.eurostat.ec.europa.eu/portal/page/portal/sdi/indicators>. (*Tables of EU Indices of sustainability.*)
- Geiser, K., (2001) "Materials matter: towards a sustainable materials policy", The MIT Press, Cambridge, MA. (*A monograph examining the historical and present-day actions and attitudes relating to material conservation, with informative discussion of renewable materials, material efficiency, and dematerialization.*)
- Goldberg, L.H. (Editor), (1999) "Green electronics/green bottom line", Newness.
- Guidice, F., La Rosa, G., and Risitano, A., (2006) "Product design for the environment" CRC/Taylor and Francis, London, UK. (*A well-balanced review of current thinking on eco-design.*)
- Imhoff, D., (2005) "Paper or plastic: searching for solutions to an overpackaged world", University of California Press. (*What it says: a study of packaging taking a critical stance.*)
- IPCC, (2007) "Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change", Pachauri, R.K. and Reisinger, A. (Eds.) IPCC, Geneva, Switzerland, <http://www.ipcc.ch>. (*The report asserts that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."*)
- IPCC, (2014) IPCC, Geneva, Switzerland, <http://www.ipcc.ch>. (*The Report, presented in Copenhagen, Denmark in 2014, will provide an update of knowledge on the scientific, technical and socio-economic aspects of climate change.*)
- Lovelock, J., (2000) "Gaia, a new look at life on earth", Oxford University Press, Oxford, UK. (*A visionary statement of man's place in the environment.*)
- MacKay, D.J.C., (2008) "Sustainable energy – without the hot air", Department of Physics, Cambridge University, Cambridge, UK. www.withouthotair.com/. (*MacKay brings a welcome dose of common sense into the discussion of energy sources and use. Fresh air replacing hot air.*)
- Malthus, T. R. (1798), "An essay on the principle of population", London, Printed for Johnson, St. Paul's Church-yard. (<http://www.ac.wvu.edu/~stephan/malthus/malthus>.) (*The originator of the proposition that population growth must ultimately be limited by resource availability.*)

- Meadows, D.H., Meadows, D.L., Randers, J., and Behrens, W.W., (1972) "The limits to growth", Universe Books, New York. (*The "Club of Rome" report that triggered the first of a sequence of debates in the 20th century on the ultimate limits imposed by resource depletion.*)
- Meadows, D.H., Meadows, D.L. and Randers, J., (1992) "Beyond the limits", Earthscan, London, UK. (*The authors of "The Limits to Growth" use updated data and information to restate the case that continued population growth and consumption might outstrip the Earth's natural capacities.*)
- Mrityunjay, S., Tatsuki, O., and Rajiv, A. (Editors), (2015), "Green and sustainable manufacturing of advanced materials", Elsevier.
- Mulder, K. (Editor), (2006) "Sustainable development for engineers: a handbook and resource guide", Greenleaf Publishing Ltd., Sheffield, UK.
- Nielsen, R., (2005) "The little green handbook", Scribe Publications Pty Ltd, Carlton North, Victoria, Australia. (*A cold-blooded presentation and analysis of hard facts about population, land and water resources, energy, and social trends.*)
- Schmidt-Bleek, F., (1997) "How much environment does the human being need – factor 10 – the measure for an ecological economy", Deutscher Taschenbuchverlag, Munich, Germany. (*Both Schmidt-Bleek and von Weizsäcker, referenced below, argue that sustainable development will require a drastic reduction in material consumption.*)
- Tolley, R., (Editor), (2003) "Sustainable transport", Woodhead Publishing.
- US Department of Energy, (2010), "Critical materials strategy for clean technology", www.energy.gov/news/documents/criticalmaterialsstrategy.pdf. (*A report on the role of rare earth elements and other materials in low-carbon energy technology.*)
- US Department of Energy, (2010) "Critical materials strategy", Office of Policy and International Affairs, materialstrategy@hq.doe.gov, www.energy.gov. (*A broader study than MRS 2010, above, but addressing many of the same issues of material critical to the energy, communication and defense industries, and the priorities for securing adequate supply.*)
- USGS, (2002) Circular 2112 "Materials in the economy –material flows, scarcity and the environment", by L.W. Wagner, US Department of the Interior (www.usgs.gov). (*A readable and perceptive summary of the operation of the material supply chain, the risks to which it is exposed, and the environmental consequences of material production.*)
- UNEP, (1972) Report of the United Nations Conference on Human Environment, Stockholm. The Earth Summit, <http://www.unep.org/Documents/Multilingual/Default.asp?DocumentID=97>. (*The conference, known as the Earth Summit, put environmental issues on the international agenda for the first time and laid the groundwork for progress in the environment and development.*)

- Visser, W., (2009) "The top 50 sustainability books", (The University of Cambridge Programme for Sustainability Leadership), Greenleaf Publishing. *(Four-page précis of key books on sustainability, each listing key ideas, a synopsis and author notes.)*
- von Weizsäcker, E., Lovins, A.B., and Lovins, L.H., (1997) "Factor four: doubling wealth, halving resource use", Earthscan Publications, London, UK. *(Both von Weizsäcker and Schmidt-Bleek referenced above, argue that sustainable development will require a drastic reduction in material consumption.)*
- WCED, (1987) Report of the World Commission on the Environment and Development, Oxford University Press, Oxford, UK. *(The so-called Brundtland report launched the current debate and stimulated current actions on moving towards a sustainable existence.)*
- World Bank Development Indicators, (2012) <http://data.worldbank.org/data-catalog/world-development-indicators>. *(The World Bank assembles annual figures for global economic development data at the national, regional, and global levels.)*
- WSSD, (2002) World Summit on Sustainable Development, Johannesburg, <http://www.who.int/trade/glossary/story097/en/index.html>. *(The summit identified five priorities for sustainable development: water, energy, health, agriculture and biodiversity.)*

14.9 Appendix: Software to support social life-cycle assessment

Tools for environmental life-cycle assessment (Chapter 3 and its appendix) have evolved along two paths, one insisting on rigor and adherence to a rigid process, the other, less rigorous but far faster and filling different functions: that of providing the quick feedback that a designer needs for immediate action and that of education, allowing involvement in the steps without the need to master a complex process. Tools for S-LCA, though all much younger, are evolving along a similar path. They include the following:

- Social Hotspots Database (<https://www.socialhotspot.org/>): An S-LCA tool developed by PRÉ Consultants, now connected with SimaPro, their LCA package
- The Roundtable for Product Social Metrics (<https://product-social-impact-assessment.com/roundtable-for-product-social-metrics/>): A roundtable sharing methods, and case studies, hosted by PRÉ Sustainability
- The Sustainability Consortium (<https://www.sustainabilityconsortium.org/>): The Sustainability Consortium is a global nonprofit organization developing a sustainability toolkit known as THESIS (The Sustainability Insight System)

- Gapminder (<https://www.gapminder.org/>): Website with engaging educational tools demonstrating the evolution of social metrics over time
- LIFE: FORTUNE (<https://www.fortune-life.eu/portfolio/b-1-design-of-a-dynamic-lcalccslca-tool/>): Design of a dynamic LCA + life-cycle costing + S-LCA tool, under development
- The CES EduPack social hot spot analysis tool: An Excel-based tool that illustrates the S-LCA method and allows case studies. It is easy to use and well suited to teaching, available from www.Grantadesign.com/Education

14.10 Exercises

E14.1. History of sustainability thinking. The UN Brundtland Report of 1987 (Section 14.1) initiated international efforts to establish a more sustainable future. Visionary thinkers at earlier times had raised concerns that seeded the UN decision to initiate the report. Use the Internet to explore the dates and views expressed in one of the three influential writings listed below:

- Thomas Malthus, in *An Essay on the Principle of Population*
- Meadows, D.H., et al., in *The Limits to Growth*
- Rachel Carson, in *Silent Spring*

E14.2. Regroup the UN sustainable development goals of Fig. 14.2 under the headings “Financial and Manufactured Capital,” “Environmental Capital,” and “Social and Human Capital.” Information about each goal is most easily found in the Sustainable Development Goals Report:

<https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019.pdf>.

E14.3. What is the history and remit of the Intergovernmental Panel on Climate Change? Explore its website (www.IPCC.ch) to find out.

E14.4. The global financial crisis that started with the collapse of Lehman Brothers in 2008 had impacts on all three capitals. Can you suggest at least one impact for each?

E14.5. “Growth” is seen as desirable in a market economy because it contributes to manufactured and financial capital. Can you think of things that contribute to one or another of the capitals by *not* growing or, better, by shrinking?

E14.6. Compare the relative ecological footprints, GDPs, and HDIs per capita of the people of Qatar and Singapore, two wealthy Asian nations. Values for each can be read from Figs. 14.4–14.6. What do the numbers suggest about how these nations deploy their wealth?

E14.7. Compare the relative ecological footprints, GDPs, and HDIs per capita of the people of Luxemburg and Norway, two wealthy European nations. Values for each can be read from Figs. 14.4–14.6. What do the numbers suggest about how these nations deploy their wealth?

E14.8. The current (2017) growth rate of the population in India has fallen to 1.1% per year. Its GDP per capita is growing at 5.4% per year. Assuming that population P , affluence A (measured by GDP), and technology T are mutually independent, what change in resource intensity (meaning environmental impact per unit of GDP) must be achieved by technological development in India to ensure that environmental impact I gets no worse than it already is?

E14.9. Many Chinese cities have severe air pollution problems. The current (2019) growth rate of population in China is 0.6% per year. Its GDP per capita is growing at 9.1% per year. Assuming that population P , affluence A (measured by GDP), and technology T are mutually independent, what change in resource intensity (meaning environmental impact per unit of GDP) must be achieved by technological development in China to ensure that environmental impact I gets no worse than it already is?

E14.10. The population of Bahrain, with one of the world's largest GDPs per capita, is growing at 4.6% per year and its GDP is growing at over 3.5% per year (2017 data). Assuming that population P , affluence A (measured by GDP), and technology T are mutually independent, what rate of technological improvement will be required in Bahrain to avoid an increasing impact I on global natural resources?

E14.11. Use the Internet to find the growth rate of population P and of GDP (a proxy for affluence, A) in Luxemburg. What rate of technological advance T will be needed to ensure that the ecological impact of Luxemburg does not exceed its current level?

E14.12. The summary page of the Jaguar Land Rover 2019 SR (<https://www.landrover.co.uk/explore-land-rover/responsibility/environmental-responsibility.html>) lists achievements over a 12-year period. They include:

- operational carbon emissions per vehicle, down by 21%
 - water use per vehicle, down by 17%
- (a) These are examples of reductions in impact, I , achieved by improved technology T . What rates change of T in percentage per year, do these represent?
 - (b) Jaguar Land Rover has global sales. The biggest market is China. The current (2019) growth rate of population in China is 0.6% per year. Its GDP is growing at 6.1% per year. If car sales increase in proportion to population and affluence, are the technical advances made by Jaguar Land

Rover sufficient to offset the growing resource demands of Chinese sales?

E14.13. Scientific skepticism is healthy. Many scientists and politicians now accept that the global climate is changing, and that this is caused, in part, by industrial society and that nations should collaborate to counter it. But there are those who disagree. Their views should not be dismissed without considering what they have to say. Use the Internet to identify individuals and groups that argue that climate change is not happening or is not human-made, or that it is unimportant.

E14.14. An influential investor in a small company making household products insists that the company issue an SR following the GRI guidelines. Briefly, what is the GRI?

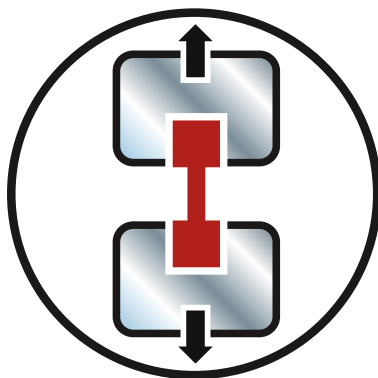
E14.15. The website CSRwire (<https://www.csrwire.com/reports>) gives access to SRs from a large number of companies. Select one of the companies that either provides or uses materials, survey the report, and write a half-page summary like that of the examples in the text of what you find.

Appendix A—Material property data

Version 5, March 1, 2020

This appendix lists the general, mechanical, thermal, and electrical properties of the materials that appear in the charts, examples, and exercises of the text. Each property has a range of values, often wide; they appear as the lengths of the bars and dimensions of the bubbles on the charts in the main text (Figs. 9.2–9.6 for example). In the tables that follow, the ranges are reduced to single indicative “point” values, the averages of the ranges. Each table starts with a schematic illustrating the span of values for the properties it contains, separated by material class.

Eco-properties are listed in Appendix B



CONTENTS

Table A1. Material names and applications

Table A2. Density and price

Table A3. Young's modulus and yield strength or hardness

Table A4. Tensile strength and fracture toughness

Table A5. Melting temperature, glass temperature, and specific heat

Table A6. Thermal conductivity and thermal expansion

Table A7. Electrical resistivity and dielectric constant

Table A8. Fibers: density and price

Table A9. Fibers: modulus and strength

Table A1. Material names and applications

Metals	Applications
<i>Ferrous metals</i>	
Cast irons	Automotive parts, engine blocks, machine tool structural parts, lathe beds
High-carbon steels	Cutting tools, springs, bearings, cranks, shafts, railway track
Medium-carbon steels	General mechanical engineering (tools, bearings, gears, shafts, bearings)
Low-carbon steels	Steel structures (“mild steel”): bridges, oil rigs, ships; reinforcement for concrete; automotive parts, car body panels; galvanized sheet; packaging (cans, drums)
Low-alloy steels	Springs, tools, ball bearings, automotive parts (gears connecting rods, etc.)
Stainless steels	Transport, chemical and food processing plants, nuclear plants, domestic ware (cutlery, washing machines, stoves), surgical implements, pipes, pressure vessels, liquid gas containers
<i>Nonferrous metals</i>	
Aluminum alloys	
Casting alloys	Automotive parts (cylinder blocks), domestic appliances (irons)
Non-heat-treatable alloys	Electrical conductors, heat exchangers, foil, tubes, saucepans, beverage cans, lightweight ships, architectural panels
Heat-treatable alloys	Aerospace engineering, automotive bodies and panels, lightweight structures, ships
Copper alloys	Electrical conductors and wire, electronic circuit boards, heat exchangers, boilers, cookware, coinage, sculptures
Lead alloys	Roof and wall cladding, solder, X-ray shielding, battery electrodes
Magnesium alloys	Automotive castings, wheels, general lightweight castings for transport, nuclear fuel containers; principal alloying addition to aluminum alloys
Nickel alloys	Gas turbines and jet engines, thermocouples, coinage; alloying addition to austenitic stainless steels
Titanium alloys	Aircraft turbine blades; general structural aerospace applications; biomedical implants
Zinc alloys	Die castings (automotive, domestic appliances, toys, handles); coating on galvanized steel

Ceramics		Applications
Glasses		
Borosilicate glass		Ovenware, laboratory ware, headlights
Glass ceramic		Cookware, lasers, telescope mirrors
Silica glass		High-performance windows, crucibles, high-temperature applications
Soda-lime glass		Windows, bottles, tubing, light bulbs, pottery glazes
Technical		
Alumina		Cutting tools, spark plugs, microcircuit substrates, valves
Aluminum nitride		Microcircuit substrates and heat sinks
Boron carbide		Lightweight armor, nozzles, dies, precision tool parts
Silicon		Microcircuits, semiconductors, precision instruments, infrared windows, microelectromechanical systems
Silicon carbide		High-temperature equipment, abrasive polishing grits, bearings, armor
Silicon nitride		Bearings, cutting tools, dies, engine parts
Tungsten carbide		Cutting tools, drills, abrasives
Nontechnical		
Brick		Buildings
Concrete		General civil engineering construction
Stone		Buildings, architecture, sculpture
Polymers		Applications
Elastomers		
Butyl rubber		Tires, seals, antivibration mountings, electrical insulation, tubing
Ethylene vinyl acetate	EVA	Bags, films, packaging, gloves, insulation, running shoes
Isoprene	IR	Tires, inner tubes, insulation, tubing, shoes
Natural rubber	NR	Gloves, tires, electrical insulation, tubing
Polychloroprene (neoprene)	CR	Wetsuits, O-rings and seals, footwear

(Continued)

Polyurethane elastomers	eI-PU	Packaging, hoses, adhesives, fabric coating
Silicone elastomers		Electrical insulation, electronic encapsulation, medical implants
<i>Thermoplastics</i>		
Acrylonitrile butadiene styrene	ABS	Communication, appliances, automotive interiors, luggage, toys, boats
Cellulose polymers	CA	Tool and cutlery handles, decorative trim, pens
Ionomer	I	Packaging, golf balls, blister packs, bottles
Polyamides (nylons)	PA	Gears, bearings, plumbing, packaging, bottles, fabrics, textiles, ropes
Polycarbonate	PC	Safety goggles, shields, helmets, light fittings, medical components
Polyether ether ketone	PEEK	Electrical connectors, racing car parts, fiber composites
Polyethylene	PE	Packaging, bags, squeeze tubes, toys, artificial joints
Polyethylene terephthalate	PET	Blow-molded bottles, film, audio/video tape, sails
Polymethyl methacrylate	PMMA	Aircraft windows, lenses, reflectors, lights, compact discs
Polyoxymethylene (acetal)	POM	Zips, domestic and appliance parts, handles
Polypropylene	PP	Ropes, garden furniture, pipes, kettles, electrical insulation, AstroTurf
Polystyrene	PS	Toys, packaging, cutlery, audio cassette/compact disc cases
Polyurethane thermoplastics	tpPU	Cushioning, seating, shoe soles, hoses, car bumpers, insulation
Poly(vinyl chloride)	PVC	Pipes, gutters, window frames, packaging
Polytetrafluoroethylene (Teflon)	PTFE	Nonstick coatings, bearings, skis, electrical insulation, tape

Thermosets

Epoxies	EP	Adhesives, fiber composites, electronic encapsulation
Phenolics	PHEN	Electrical plugs, sockets, cookware, handles, adhesives
Polyester	PEST	Furniture, boats, sporting goods

Polymer foams

Flexible polymer foam	Packaging, buoyancy, cushioning, sponges, sleeping mats
Rigid polymer foam	Thermal insulation, sandwich panels, packaging, buoyancy

Composites**Applications**

CFRP	Lightweight structural parts (aerospace, bike frames, sporting goods, boat hulls and oars, springs)
GFRP	Boat hulls, automotive parts, chemical plant

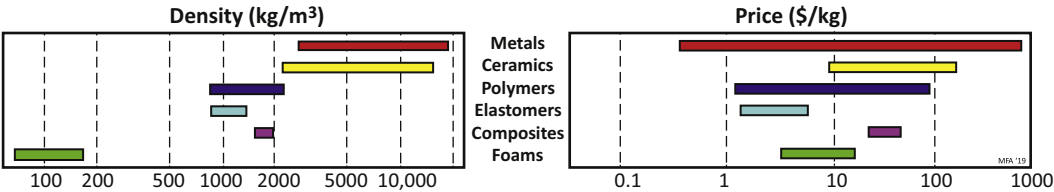
Natural materials**Applications**

Bamboo	Building, scaffolding, paper, ropes, baskets, furniture
Cork	Corks and bungs, seals, floats, packaging, flooring
Leather	Shoes, clothing, bags, drive belts
Wood	Construction, flooring, doors, furniture, packaging, sporting goods

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

Table A2. Density and price

The densities of materials fall into three broad bands. Metals and ceramics are relatively dense. Polymers and polymer–matrix composites are less so. Foams are the least dense of all.



	Metals	Density (kg/m ³)	Price (US\$/kg)
Ferrous metals	Cast iron	7100	0.36
	High-carbon steel	7800	0.76
	Low-alloy steel	7800	0.84
	Low-carbon steel	7800	0.76
	Stainless steel	7700	3.1
Nonferrous metals	Aluminum alloys	2800	4.3
	Copper alloys	8300	5.6
	Lead alloys	11,000	2.9
	Magnesium alloys	1800	2.4
	Nickel alloys	8400	15
	Silver	11,000	540
	Tin	7300	18
	Titanium alloys	4600	24
	Tungsten alloys	1.8×10^4	62
	Zinc alloys	6600	3.4

	Ceramics	Density (kg/m ³)	Price (US\$/kg)
Glasses	Borosilicate glass (Pyrex)	2200	5.4
	Silica glass	2200	7.4
	Soda-lime glass	2500	1.5
Technical ceramics	Alumina	3700	25
	Aluminum nitride	3300	130
	Silicon	2300	11
	Silicon carbide	3200	16
	Tungsten carbides	16,000	22
	Zirconia	6000	21
Nontechnical ceramics	Brick	2000	1
	Cement	2000	0.11
	Concrete	2400	0.05
	Stone	2400	0.5

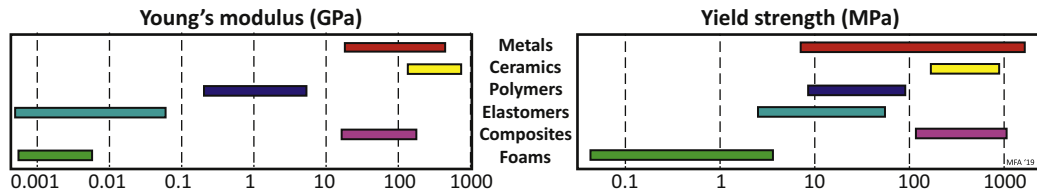
	Polymers	Density (kg/m ³)	Price (US\$/kg)
Elastomers	Butyl rubber (IIR)	930	2.3
	Ethylene vinyl acetate (EVA)	950	1.8
	Natural rubber	950	1.6
	Polychloroprene (neoprene)	1300	4.7
	Polyisoprene	930	2.4
	Polyurethane	1200	2.3
	Silicone elastomers	1100	5.4
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	1000	3
	Cellulose polymers (CA)	990	5.5
	Ionomer (I)	940	3.2
	Polyamides (nylons, PA)	1100	4.1
	Polycarbonate (PC)	1200	3.4
	Polyether ether ketone (PEEK)	1300	92
	Polyethylene (PE)	950	1.6
	Polyethylene terephthalate (PET)	1300	1.4
	Poly lactide (PLA)	1300	3.2
	Polymethyl methacrylate (PMMA)	1200	4.3
	Polyoxymethylene (acetal, POM)	1400	2.9
	Polypropylene (PP)	900	1.4
	Polystyrene (PS)	1000	2.2
	Polytetrafluoroethylene (Teflon, PTFE)	2200	13
	Polyurethane (tpPUR)	1200	4.7
	Poly(vinyl chloride) (tpPVC)	1400	2.6
	Thermoplastic starch (TPS)	1300	2.8
Thermosets	Epoxies	1200	2.6
	Phenolics	1300	1.8
	Polyester	1200	4.1

Foams	Flexible polymer foam (MD)	90	2.7
	Rigid polymer foam (MD)	110	15
	Composites	Density (kg/m³)	Price (US\$/kg)
Isotropic	CFRP, epoxy matrix	1500	36
	GFRP, epoxy matrix	1900	27
	Natural	Density (kg/m³)	Price (US\$/kg)
Wood-based	Paper and cardboard	942	1.1
	Softwood	510	0.88
	Hardwood	940	8.5

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

Table A3. Young’s modulus and yield strength or hardness

Metals and ceramics are both stiff and strong. Polymers are much less stiff, but their strengths overlap with those of metals. Elastomers are distinguished by their exceptionally low stiffness. The yield strength is listed for metals and polymers, the Vickers hardness for ceramics and glasses.



	Metals	Young's modulus (GPa)	Yield strength (MPa)
Ferrous metals	Cast iron	170	390
	High-carbon steel	210	630
	Low-alloy steel	200	870
	Low-carbon steel	210	300
	Stainless steel	200	540
Nonferrous metals	Aluminum alloys	72	350
	Copper alloys	100	170
	Lead alloys	15	25
	Magnesium alloys	44	120
	Nickel alloys	210	410
	Silver	71	240
	Tin	43	10
	Titanium alloys	110	870
	Tungsten alloys	340	780
	Zinc alloys	83	160
	Ceramics	Young's modulus (GPa)	Vickers hardness (HV)
Glasses	Borosilicate glass (Pyrex)	62	700
	Silica glass	71	650
	Soda-lime glass	70	460
Technical ceramics	Alumina	320	1200
	Aluminum nitride	330	1100
	Silicon	150	1000
	Silicon carbide	430	2400
	Tungsten carbides	660	2800
	Zirconia	220	1100
Nontechnical ceramics	Brick	22	29
	Cement	41	5.9
	Concrete	19	6
	Stone	19	16

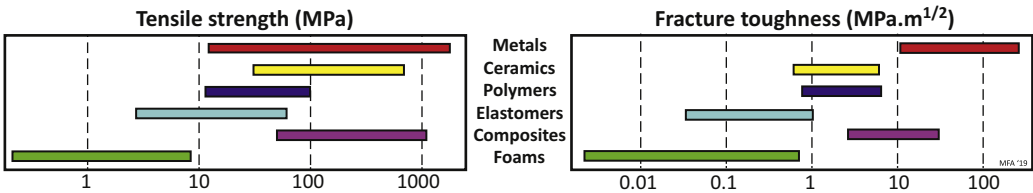
	Polymers	Young's modulus (GPa)	Yield strength (MPa)
Elastomers	Butyl rubber (IIR)	0.001	4.9
	Ethylene vinyl acetate (EVA)	0.02	15
	Natural rubber	0.0016	24
	Polychloroprene (neoprene)	0.0019	17
	Polyisoprene	0.0024	22
	Polyurethane	0.0086	45
	Silicone elastomers	0.016	9
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	2.4	41
	Cellulose polymers (CA)	1.7	26
	Ionomer (I)	0.29	11
	Polyamides (nylons, PA)	1.4	50
	Polycarbonate (PC)	2.4	62
	Polyether ether ketone (PEEK)	3.8	79
	Polyethylene (PE)	0.75	23
	Polyethylene terephthalate (PET)	2.9	52
	Poly lactide (PLA)	3.4	63
	Polymethyl methacrylate (PMMA)	2.7	62
	Polyoxymethylene (acetal, POM)	2.9	59
	Polypropylene (PP)	1.2	28
	Polystyrene (PS)	2.7	34
	Polytetrafluoroethylene (Teflon, PTFE)	0.47	21
	Polyurethane (tpPUR)	1.6	46
	Poly(vinyl chloride) (tpPVC)	2.6	41
	Thermoplastic starch (TPS)	0.6	19
Thermosets	Epoxies	2.4	51
	Phenolics	3.7	37
	Polyester	3	36

Foams	Flexible polymer foam (MD)	0.007	0.18
	Rigid polymer foam (MD)	0.18	1.2
	Composites	Young's modulus (GPa)	Yield strength (MPa)
Isotropic	CFRP, epoxy matrix	100	760
	GFRP, epoxy matrix	20	150
	Natural	Young's modulus (GPa)	Yield strength (MPa)
Wood-based	Paper and cardboard	2.8	23
	Softwood	9.3	40
	Hardwood	23	48

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

Table A4. Tensile strength and fracture toughness

Metals have both high strength and high fracture toughness, K_{Ic} . Composites lie lower but still have useful values of both. The low fracture toughness of ceramics and glasses makes design with them more difficult. Polymers appear to be as brittle as ceramics, but their toughness $(K_{Ic})^2/E$ is comparable to that of metals.



	Metals	Tensile strength (MPa)	Fracture toughness (MPa · m ^{1/2})
Ferrous metals	Cast iron	600	35
	High-carbon steel	1000	50
	Low-alloy steel	1100	56
	Low-carbon steel	450	57
	Stainless steel	820	88
Nonferrous metals	Aluminum alloys	410	32
	Copper alloys	380	57
	Lead alloys	37	16
	Magnesium alloys	180	15
	Nickel alloys	680	94
	Silver	290	62
	Tin	14	21
	Titanium alloys	950	66
	Tungsten alloys	1000	130
	Zinc alloys	260	19
	Ceramics	Tensile strength (MPa)	Fracture toughness (MPa · m ^{1/2})
Glasses	Borosilicate glass (Pyrex)	27	0.65
	Silica glass	84	0.69
	Soda-lime glass	33	0.59
Technical ceramics	Alumina	240	3.6
	Aluminum nitride	230	2.8
	Silicon	170	0.88
	Silicon carbide	490	4.1
	Tungsten carbides	450	2.8
	Zirconia	600	6.9

(Continued)

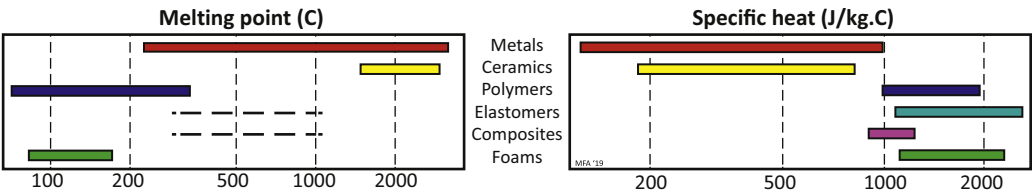
Nontechnical ceramics	Brick	9.8	1.4
	Cement	2	0.4
	Concrete	1.2	0.4
	Stone	9.4	0.88
	Polymers	Tensile strength (MPa)	Fracture toughness (MPa·m ^{1/2})
Elastomers	Butyl rubber (IIR)	4.9	0.064
	Ethylene vinyl acetate (EVA)	18	0.59
	Natural rubber	24	0.14
	Polychloroprene (neoprene)	17	0.17
	Polyisoprene	22	0.084
	Polyurethane	45	0.5
	Silicone elastomers	9	0.35
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	44	2.5
	Cellulose polymers (CA)	26	1.6
	Ionomer (I)	25	2
	Polyamides (nylons, PA)	55	3.5
	Polycarbonate (PC)	67	2.2
	Polyether ether ketone (PEEK)	85	3.4
	Polyethylene (PE)	30	1.6
	Polyethylene terephthalate (PET)	57	5
	Poly lactide (PLA)	57	4
	Polymethyl methacrylate (PMMA)	59	1.1
	Polyoxymethylene (Acetal, POM)	73	4
	Polypropylene (PP)	34	3.7
	Polystyrene (PS)	43	0.88

	Polytetrafluoroethylene (Teflon, PTFE)	27	1.5
	Polyurethane (tpPUR)	44	3
	Poly(vinyl chloride) (tpPVC)	41	3.7
	Thermoplastic starch (TPS)	19	1
	Thermosets	Epoxies	63
Phenolics		46	0.98
Polyester		61	1.4
Foams	Flexible polymer foam (MD)	1.1	0.05
	Rigid polymer foam (MD)	1.8	0.02
	Composites	Tensile strength (MPa)	Fracture toughness (MPa · m ^{1/2})
Isotropic	CFRP, epoxy matrix	760	11
	GFRP, epoxy matrix	180	13
	Natural	Tensile strength (MPa)	Fracture toughness (MPa · m ^{1/2})
Wood-based	Paper and cardboard	34	2.4
	Softwood	77	3.7
	Hardwood	150	9.9

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

Table A5. Melting temperature, glass temperature, and specific heat

Metals and ceramics have high melting points and low specific heats. Polymers have the reverse. Elastomers and composites with thermosetting polymer matrices decompose before they melt.



	Metals	T_m or T_g ($^{\circ}\text{C}$)	Specific heat ($\text{J/kg}\cdot^{\circ}\text{C}$)
Ferrous metals	Cast iron	1200	480
	High-carbon steel	1400	480
	Low-alloy steel	1500	480
	Low-carbon steel	1500	480
	Stainless steel	1400	480
Nonferrous metals	Aluminum alloys	570	940
	Copper alloys	940	380
	Lead alloys	290	130
	Magnesium alloys	540	1000
	Nickel alloys	1400	440
	Silver	960	230
	Tin	230	220
	Titanium alloys	1600	540
	Tungsten alloys	3100	130
	Zinc alloys	380	420
	Ceramics	T_m or T_g ($^{\circ}\text{C}$)	Specific heat ($\text{J/kg}\cdot^{\circ}\text{C}$)
Glasses	Borosilicate glass (Pyrex)	520	780
	Silica glass	1200	700
	Soda-lime glass	510	900
Technical ceramics	Alumina	2100	770
	Aluminum nitride	2500	790
	Silicon	1400	690
	Silicon carbide	2300	730
	Tungsten carbides	2900	230
	Zirconia	2600	500
Nontechnical ceramics	Brick	1100	800
	Cement	1100	840
	Concrete	1100	940
	Stone	1300	880

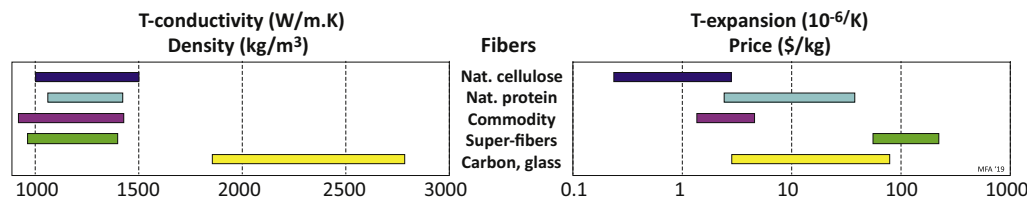
	Polymers	T _m or T _g (°C)	Specific heat (J/kg·°C)
Elastomers	Butyl rubber (IIR)	−68	1900
	Ethylene vinyl acetate (EVA)	−41	2100
	Natural rubber	−70	1900
	Polychloroprene (neoprene)	−42	2100
	Polyisoprene	−81	2100
	Polyurethane	−40	1700
	Silicone elastomers	−65	1100
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	110	1700
	Cellulose polymers (CA)	110	1400
	Ionomer (I)	44	1800
	Polyamides (nylons, PA)	54	1500
	Polycarbonate (PC)	150	1200
	Polyether ether ketone (PEEK)	170	1500
	Polyethylene (PE)	−110	1800
	Polyethylene terephthalate (PET)	14	1200
	Poly lactide (PLA)	56	1200
	Polymethyl methacrylate (PMMA)	10	1500
	Polyoxymethylene (acetal, POM)	−12	1400
	Polypropylene (PP)	−20	1900
	Polystyrene (PS)	95	1200
	Polytetrafluoroethylene (Teflon, PTFE)	120	1000
	Polyurethane (tpPUR)	74	1600
	Poly(vinyl chloride) (tpPVC)	84	1000
	Thermoplastic starch (TPS)	14	1600

Thermosets	Epoxies	130	1200
	Phenolics	210	1500
	Polyester	180	1500
Foams	Flexible polymer foam (MD)	−40	2000
	Rigid polymer foam (MD)	100	1500
	Composites	T_m or T_g (°C)	Specific heat (J/kg·°C)
Isotropic	CFRP, epoxy matrix	130	970
	GFRP, epoxy matrix	130	1100
	Natural	T_m or T_g (°C)	Specific heat (J/kg·°C)
Wood-based	Paper and cardboard	—	1300
	Softwood	—	1700
	Hardwood	—	1700

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

Table A6. Thermal conductivity and thermal expansion

Metals and some ceramics conduct heat well. Polymers, foams, and composites insulate. Materials with high melting points (refractory metals and ceramics) have low expansion coefficients. Those with low melting points (notable polymers) expand greatly when heated.



	Metals	T-conductivity (W/m/K)	T-expansion ($10^{-6}/^{\circ}\text{C}$)
Ferrous metals	Cast iron	36	11
	High-carbon steel	50	12
	Low-alloy steel	43	12
	Low-carbon steel	52	12
	Stainless steel	19	13
Nonferrous metals	Aluminum alloys	160	24
	Copper alloys	120	19
	Lead alloys	31	28
	Magnesium alloys	79	26
	Nickel alloys	12	13
	Silver	420	20
	Tin	61	23
	Titanium alloys	7.3	9
	Tungsten alloys	91	4.9
	Zinc alloys	110	27
	Ceramics	T-conductivity (W/m/K)	T-expansion ($10^{-6}/^{\circ}\text{C}$)
Glasses	Borosilicate glass (Pyrex)	1.1	3.6
	Silica glass	1.4	0.64
	Soda-lime glass	0.95	9.3
Technical ceramics	Alumina	25	7.2
	Aluminum nitride	170	4.7
	Silicon	140	2.5
	Silicon carbide	100	4.4
	Tungsten carbides	70	6.1
	Zirconia	2.9	11
Non-technical ceramics	Brick	0.57	9.4
	Cement	0.85	18
	Concrete	1.3	7.7
	Stone	2.1	13

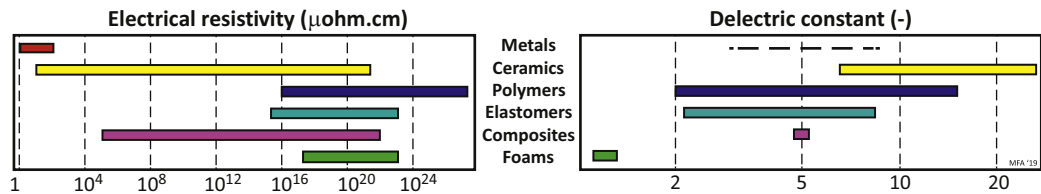
	Polymers	T-conductivity (W/m/K)	T-expansion (10 ⁻⁶ /°C)
Elastomers	Butyl rubber (IIR)	0.1	180
	Ethylene vinyl acetate (EVA)	0.35	170
	Natural rubber	0.14	220
	Polychloroprene (neoprene)	0.17	220
	Polyisoprene	0.11	260
	Polyurethane	0.29	160
	Silicone elastomers	0.25	270
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	0.26	95
	Cellulose polymers (CA)	0.14	120
	Ionomer (I)	0.26	230
	Polyamides (nylons, PA)	0.24	130
	Polycarbonate (PC)	0.21	120
	Polyether ether ketone (PEEK)	0.25	120
	Polyethylene (PE)	0.42	160
	Polyethylene terephthalate (PET)	0.14	120
	Poly lactide (PLA)	0.14	140
	Polymethyl methacrylate (PMMA)	0.2	120
	Polyoxymethylene (acetal, POM)	0.23	150
	Polypropylene (PP)	0.14	150
	Polystyrene (PS)	0.13	120
	Polytetrafluoroethylene (Teflon, PTFE)	0.25	140
	Polyurethane (tpPUR)	0.24	110
	Poly(vinyl chloride) (tpPVC)	0.18	73
	Thermoplastic starch (TPS)	0.17	210
Thermosets	Epoxies	0.19	97
	Phenolics	0.15	120
	Polyester	0.29	130

Foams	Flexible polymer foam (MD)	0.057	160
	Rigid polymer foam (MD)	0.03	37
	Composites	T-conductivity (W/m/K)	T-expansion ($10^{-6}/^{\circ}\text{C}$)
Isotropic	CFRP, epoxy matrix	1.8	2
	GFRP, epoxy matrix	0.47	17
	Natural	T-conductivity (W/m/K)	T-expansion ($10^{-6}/^{\circ}\text{C}$)
Wood-based	Paper and cardboard	0.24	10
	Softwood	0.26	4.7
	Hardwood	0.45	4.7

CFRP, carbon-fiber-reinforced polymer; *GFRP*, glass-fiber-reinforced polymer.

Table A7. Electrical resistivity and dielectric constant

Metals and a few ceramics conduct electricity well. All other materials are non-conductors. Some ceramics and polymers have high dielectric constants because they polarize in a field. Foams have a low constant because they are mostly gas (dielectric constant 1).



	Metals	Resistivity ($\mu\text{ohm} \cdot \text{cm}$)	Dielectric constant (-)
Ferrous metals	Cast iron	52	na
	High-carbon steel	18	na
	Low-alloy steel	23	na
	Low-carbon steel	17	na
	Stainless steel	75	na
Nonferrous metals	Aluminum alloys	4.4	na
	Copper alloys	7	na
	Lead alloys	24	na
	Magnesium alloys	9.1	na
	Nickel alloys	110	na
	Silver	1.7	na
	Tin	11	na
	Titanium alloys	160	na
	Tungsten alloys	11	na
	Zinc alloys	6.4	na
	Ceramics	Resistivity ($\mu\text{ohm} \cdot \text{cm}$)	Dielectric constant (-)
Glasses	Borosilicate glass (Pyrex)	1.0×10^{22}	5.3
	Silica glass	1.0×10^{25}	3.8
	Soda-lime glass	2.5×10^{18}	7.1
Technical ceramics	Alumina	1.0×10^{21}	9.4
	Aluminum nitride	1.0×10^{20}	8.6
	Silicon	1.0×10^9	11
	Silicon carbide	3.2×10^{10}	7.5
	Tungsten carbides	45	na
	Zirconia	7.7×10^{19}	17
Nontechnical ceramics	Brick	1.4×10^{14}	6.3
	Cement	6.6×10^{11}	9.8
	Concrete	5.8×10^{12}	9.8
	Stone	1.0×10^{12}	7.3

	Polymers	Resistivity ($\mu\text{ohm} \cdot \text{cm}$)	Dielectric constant (-)
Elastomers	Butyl rubber (IIR)	3.2×10^{22}	2.3
	Ethylene vinyl acetate (EVA)	5.6×10^{21}	2.9
	Natural rubber	3.2×10^{21}	2.5
	Polychloroprene (neoprene)	1.0×10^{18}	7.3
	Polyisoprene	3.2×10^{15}	2.7
	Polyurethane	5.7×10^{17}	6.3
	Silicone elastomers	1.2×10^{20}	2.7
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	9.9×10^{21}	3.0
	Cellulose polymers (CA)	9.9×10^{18}	5.1
	Ionomer (I)	9.9×10^{21}	2.3
	Polyamides (nylons, PA)	1.2×10^{20}	9.2
	Polycarbonate (PC)	3.2×10^{20}	3.2
	Polyether ether ketone (PEEK)	9.9×10^{21}	3.2
	Polyethylene (PE)	3.1×10^{23}	2.3
	Polyethylene terephthalate (PET)	9.9×10^{20}	3.6
	Poly lactide (PLA)	4.3×10^{17}	3.1
	Polymethyl methacrylate (PMMA)	9.9×10^{23}	3.3
	Polyoxymethylene (acetal, POM)	9.9×10^{20}	3.8
	Polypropylene (PP)	9.9×10^{22}	2.2
	Polystyrene (PS)	1.0×10^{26}	2.5
	Polytetrafluoroethylene (Teflon, PTFE)	9.9×10^{23}	2.1
	Polyurethane (tpPUR)	9.9×10^{18}	6.8
	Poly(vinyl chloride) (tpPVC)	1.0×10^{21}	3.1
	Thermoplastic starch (TPS)	1.0×10^{17}	4.5

Thermosets	Epoxies	2.4×10^{21}	4.0
	Phenolics	9.9×10^{18}	4.9
	Polyester	9.9×10^{18}	3.5
Foams	Flexible polymer foam (MD)	3.2×10^{21}	1.2
	Rigid polymer foam (MD)	1.0×10^{19}	1.1

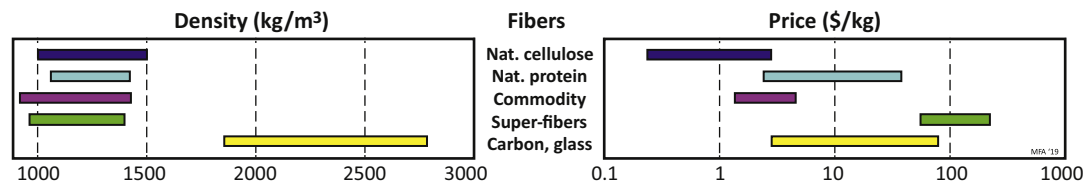
Composites		Resistivity ($\mu\text{ohm} \cdot \text{cm}$)	Dielectric constant (-)
Isotropic	CFRP, epoxy matrix	4.0×10^5	na
	GFRP, epoxy matrix	6.8×10^{21}	5

Natural		Resistivity ($\mu\text{ohm} \cdot \text{cm}$)	Dielectric constant (-)
Wood-based	Paper and cardboard	1×10^{14}	3.9
	Softwood	1.1×10^{14}	5.6
	Hardwood	1.1×10^{14}	10

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

Table A8. Fibers: density and price

Cellulose-based natural fibers have low density and low price; protein-based fibers are more expensive. Commodity synthetic polymer fibers, too, have low density and modest price; polymer super-fibers are expensive. Carbon and glass have higher density and—in the case of carbon—price.



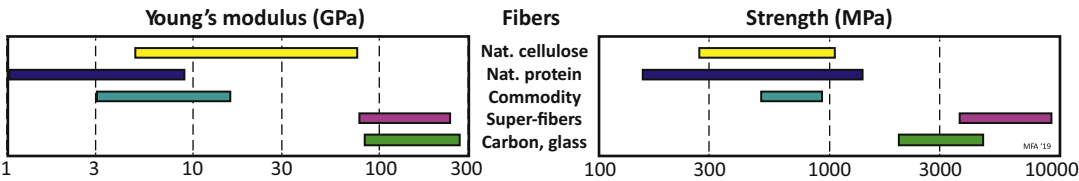
	Natural fibers	Density (kg/m ³)	Price (\$/kg)
Cellulose	Banana	1300	0.9
	Coir	1200	0.23
	Cotton	1500	3.1
	Flax	1500	1.5
	Hemp	1500	1.1
	Jute	1500	0.23
	Kenaf	1000	0.51
	Palm	1500	0.37
	Ramie	1500	1.9
	Sisal	1400	0.95
	Sugarcane	1200	1.3
Protein	Human hair	1300	—
	Silk (silkworm silk)	1300	40
	Silk (spider dragline silk)	1300	—
	Silk (spider viscid silk)	1300	—
	Wool	1300	2.9
	Human-made	Density (kg/m ³)	Price (\$/kg)
Synthetics: commodity	Acrylic (PAN)	1200	3.8
	Cellulosics (rayon)	990	3.9
	PLA (Ingeo)	1300	4.9
	Polyamide (nylon-6)	1100	3.5
	Polyester (Dacron)	1400	1.5
	Polypropylene	910	2.2
Synthetics: super-fibers	Aramid (Kevlar 49)	1400	120
	PBO (Zylon)	1500	170
	Polyarylate (Vectran)	1400	39
	UHMWPE (Spectra, Dyneema)	970	51

(Continued)

Carbon and glass	Carbon (HM carbon)	1800	74
	Carbon (HS carbon)	1800	29
	Glass (C-glass)	2600	16
	Glass (E-glass)	2600	2.3

Table A9. Fibers: modus and strength

Protein-based natural fibers have a low modulus. Cellulose-based natural fibers and commodity polymer fibers are stiffer. All three have strengths between 300 and 1000 MPa. Polymer super-fibers, carbon, and glass all have much higher modulus and strength. The super-fibers have low density, giving them particularly high values of specific stiffness and strength.



	Natural fibers	Young's modulus (GPa)	Strength (MPa)
Cellulose	Banana	28	1100
	Coir	4.9	220
	Cotton	9.2	600
	Flax	46	960
	Hemp	62	850
	Jute	31	720
	Kenaf	41	770
	Palm	11	270
	Ramie	75	910
	Sisal	15	960
	Sugarcane	22	340
Protein	Human hair	2.9	250
	Silk (silkworm silk)	11	770
	Silk (spider dragline silk)	9.9	1600
	Silk (spider viscid silk)	0.19	660
	Wool	3.4	180
	Human-made	Young's modulus (GPa)	Strength (MPa)
Synthetics	Acrylic (PAN)	18	450
	Cellulosics (rayon)	3.1	620
	PLA (Ingeo)	4.2	720
	Polyamide (nylon-6)	4.5	1200
	Polyester (Dacron)	4.3	970
	Polypropylene	16	780
Super-fibers	Aramid (Kevlar 49)	130	4000
	PBO (Zylon)	220	8600
	Polyarylate (Vectran)	60	4600
	UHMWPE (Spectra, Dyneema)	110	5000
Carbon and glass	Carbon (HM carbon)	380	2400
	Carbon (HS carbon)	240	4600
	Glass (C-glass)	68	3200
	Glass (E-glass)	78	2000

Appendix B—Eco- and supply-chain data

CONTENTS

This appendix lists eco-data for materials, processes, transport, and energy. Each property has a range of values, often wide; they appear as the lengths of the bars and dimensions of the bubbles on the charts in the main text. In the tables that follow, the ranges are reduced to single indicative “point” values, the averages of the ranges.

Data for general, mechanical, thermal, and electrical data are listed in Appendix A.



A warning. The engineering properties of materials—their mechanical, thermal, and electrical attributes—are well characterized. They are measured with sophisticated equipment according to internationally accepted standards and are reported in widely accessible handbooks and databases. They are not *exact*, but their precision—when it matters—is reported; many are known to three-figure accuracy, some to more.

The eco-properties of materials are not like that. There are no sophisticated test machines to measure embodied energies or carbon footprints. International standards, detailed in ISO 14040 and discussed in Chapter 3, lay out procedures, but

B1. Annual world production and reserves for materials

B2. Embodied energy, carbon footprint, and water demand for engineering materials

B3. Special cases: precious metals, refractive metals, and rare earths

B4. Embodied energy and carbon footprint for electronic components

B5. Embodied energies and carbon footprints of building materials

B6. Process energy and carbon footprint of processes

B7. Recycle fraction, recycle energy, and recycle carbon footprint

B8. Heat of combustion and combustion CO₂

B9. Transport: energy and carbon footprint (data sources are listed in Chapter 6)

B10. Energy: fuels and carbon-adjustment factors

B11. Energy mix by country

B12. Efficiency factors for energy conversion

these are vague and not easily applied. The differences in the process routes by which materials are made in different production facilities, the differences in energy mix in electrical power in different countries, the difficulty in setting system boundaries, and the procedural problems in assessing energy, CO₂, and the other eco-attributes all contribute to the imprecision.

So just how far can values for eco-properties be trusted? An analysis, documented in Sections 6.2 and 6.3 suggests a standard deviation of $\pm 10\%$ at best. To be significantly different, values of eco-properties must differ by *at least* 20%. The difference between materials with really large and really small values of embodied energy or carbon footprint is a factor of 1000 or more, so the imprecision still allows firm distinctions to be drawn. But when the differences are small, other factors such as the recycled content of the material, its durability (and thus lifetime), and the ability to recycle it at end of life are more significant in making the selection.

B1. Annual world production and reserves for materials

You need two things to estimate the eco-impact of material production: the eco-impact per unit (per kg or m³) and the quantity (kg, m³) produced. The carbon footprint of silver production, in kg CO_{2,eq}/kg of silver, is large, that of iron is much smaller. But the global production of silver is 27,000 tonnes per year, that of iron is 3.9 billion tonnes. An extreme example, but it makes the point. Here are some annual world production numbers. Reserves (the reported size of the accessible ore bodies, an almost meaningless quantity) are on the right.

Metals		Annual world production (millions of tonnes/year)	Reserves (millions of tonnes)
Ferrous	Iron	3900	81,000
Nonferrous metals	Aluminum	47	28,000
	Copper	19	690
	Lead	5	89
	Magnesium	1	30,000
	Nickel	2	74
	Silver	0.027	0.52
	Tin	0.3	4.7
	Titanium	0.17	15,000
	Tungsten	0.086	3.6
	Zinc	13	250
Ceramics		Annual world production (millions of tonnes/year)	Reserves (millions of tonnes)
Glass	Soda-lime glass	110	10,000
Technical ceramics	Alumina	1200	—
	Silicon	11	50,000
	Silicon carbide	1.7	—
Nontechnical ceramics	Brick	50	—
	Cement	4200	100,000
	Concrete	15,000	300,000

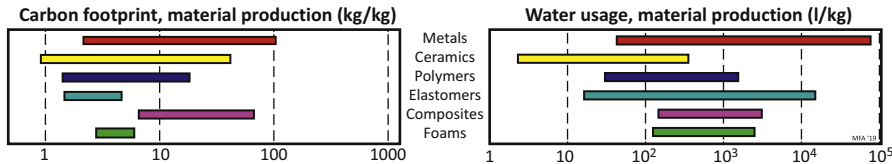
(Continued)

Ceramics		Annual world production (millions of tonnes/year)	Reserves (millions of tonnes)
Natural		Annual world production (millions of tonnes/year)	Reserves (millions of tonnes)
	Paper and cardboard	360	—
	Softwood	2000	—
Polymers		Annual world production (millions of tonnes/year)	Reserves (millions of tonnes)
Elastomers	Butyl rubber (IIR)	10	—
	Natural rubber	23	—
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	8.1	—
	Polyethylene (PE)	90	—
	Polyethylene terephthalate (PET)	19	—
	Polypropylene (PP)	62	—
	Polystyrene (PS)	19	—
	Poly(vinyl chloride) (tpPVC)	65	—
Thermosets	Epoxies	0.12	—
	Phenolics	34	—
	Polyester	40	—
Composites		Annual world production (millions of tonnes/year)	Reserves (millions of tonnes)
	CFRP, epoxy matrix (isotropic)	0.1	—
	GFRP, epoxy matrix (isotropic)	5	—

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

B2. Embodied energy, carbon footprint, and water demand for engineering materials

Embodied energy is the energy that must be committed to create 1 kg of usable material—1 kg of steel stock or of cement powder, for example. The CO₂ footprint of a material is the mass of CO₂ released into the atmosphere per unit mass of material, units kg CO_{2,eq}/kg¹. Water usage (L/kg) is what it sounds like.



Metals		Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Critical material flag ^a
Ferrous metals	Cast iron	29	2.1	45	—
	High-carbon steel	32	2.4	45	—
	Low-alloy steel	31	2.5	49	X
	Low-carbon steel	31	2.3	46	—
	Medium-carbon steel	32	2.4	47	—
	Stainless steel	73	5.4	130	X
Nonferrous metals	Aluminum alloys	190	12	1 × 10 ³	X
	Copper alloys	59	3.6	310	—
	Lead alloys	32	2.6	480	X
	Magnesium alloys	320	45	980	X
	Nickel alloys	220	12	260	X
	Silver	1500	100	76,000	—
	Tin	230	16	11,000	X

(Continued)

¹The atomic weight of carbon is 12, that of oxygen is 16, so 1 kg of carbon, when burned, produces $(12 + (2 \times 16))/12 = 3.6$ kg of CO₂.

Metals		Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Critical material flag ^a
	Titanium alloys	620	36	290	X
	Tungsten alloys	550	36	160	X
	Zinc alloys	52	4	380	—
Ceramics		Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Critical material flag ^a
Glasses	Borosilicate glass (Pyrex)	29	1.7	15	—
	Silica glass	39	2.3	1.4	—
	Soda-lime glass	11	0.76	14	—
Technical ceramics	Alumina	52	2.8	55	—
	Aluminum nitride	230	13	240	—
	Silicon	120	5	24	—
	Silicon carbide	170	7.2	58	—
	Tungsten carbides	580	38	83	X
	Zirconia	72	4	49	X
Nontechnical ceramics	Brick	3	0.24	5.5	—
	Cement	2.8	0.44	37	—
	Concrete	0.82	0.12	3.4	—
	Stone	1	0.06	3.4	—
Polymers		Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Critical material flag ^a
Elastomers	Butyl rubber (IIR)	95	4.4	110	—
	Ethylene vinyl acetate (EVA)	79	2.1	2.8	—
	Natural rubber	78	2	17,000	—
	Polychloroprene (neoprene)	64	1.5	220	—
	Polyisoprene	86	3.9	150	—
	Polyurethane	82	3.2	96	—
	Silicone elastomers	120	6.5	3.30	—
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	92	3.4	170	—
	Cellulose polymers (CA)	89	3.4	240	—
	Ionomer (I)	110	5.5	280	—

Polymers		Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Critical material flag ^a
	Polyamides (nylons, PA)	140	7	380	—
	Polycarbonate (PC)	110	4.8	170	—
	Polyether ether ketone (PEEK)	3 × 10 ₂	17	920	—
	Polyethylene (PE)	81	2.2	58	—
	Polyethylene terephthalate (PET)	82	2.7	130	—
	Poly lactide (PLA)	55	2.8	70	—
	Polymethyl methacrylate (PMMA)	100	4.9	76	—
	Polyoxymethylene (Acetal, POM)	86	3.2	250	—
	Polypropylene (PP)	80	2.9	39	—
	Polystyrene (PS)	82	2.5	150	—
	Polytetrafluoroethylene (Teflon, PTFE)	300	16	450	—
	Polyurethane (tpPUR)	82	3.2	96	—
	Poly(vinyl chloride) (tpPVC)	65	2.7	190	—
	Thermoplastic starch (TPS)	37	1.6	170	—
Thermosets	Epoxies	130	6.6	28	—
	Phenolics	77	1.9	51	—
	Polyester	71	2.5	200	—
Foams	Flexible polymer foam	90	3.2	170	—
	Rigid polymer foam	80	5.1	450	—
Composites		Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Critical material flag ^a
Isotropic	CFRP, epoxy matrix	480	35	1400	—
	GFRP, epoxy matrix	120	6'6	160	—
Natural		Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Critical material flag ^a
Wood-based	Paper and cardboard	28	0.71	1700	—
	Softwood	11	0.37	700	—
	Hardwood	12	0.6	700	—

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

^aThe **X**-flag: members of this material family may contain more than 5% of a "critical" material.

B3. Special cases: precious metals, refractive metals, and rare earths

(a) **Precious metals.** Precious metals are used in small quantities but they carry a heavy burden of embodied energy, carbon, and, of course, cost. Many have unique properties: exceptional electrical conductivity, exceptional resistance to corrosion, and exceptional functional properties as electrodes, sensors, and catalysts.

Element	Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Unique applications	Critical material flag ^a
Gold	2.5 × 10 ⁵	2.7 × 10 ⁴	2.7 × 10 ⁵	Electronics, jewelry, dentistry	—
Iridium	4.8 × 10 ⁴	2.9 × 10 ³	2 × 10 ⁵	Catalysis, electrodes, igniters	X
Osmium	6.5 × 10 ⁴	3.8 × 10 ³	1.9 × 10 ⁵	Bearings, pivots, catalysis	X
Palladium	1.9 × 10 ⁵	8.5 × 10 ³	2 × 10 ⁵	Catalysis, hydrogen purification	X
Platinum	2.9 × 10 ⁵	1.5 × 10 ⁴	2 × 10 ⁵	Catalysis, electrodes, contacts	X
Rhodium	6.1 × 10 ⁵	3 × 10 ⁴	2 × 10 ⁵	Catalysis	X
Silver	1.5 × 10 ³	1 × 10 ²	7.6 × 10 ⁴	Photosensitive compounds, dentistry	—

^aThe **X**-flag means that the element is considered to be a “critical” material.

(b) **Refractory metals.** Electric power generation, flight, and space exploration all depend on alloys that are able to work at high temperatures. Six are sufficiently important for these technologies that nations stockpile them and classify them as “critical.”

Element	Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Unique applications	Critical material flag ^a
Cobalt	130	8.3	580	High-temperature alloys, high-field magnets	X
Chromium	580	21	470	Corrosion-resistant coatings, stainless alloys	X
Molybdenum	110	7.7	360	Aerospace alloys, high-temperature components	X
Niobium	1800	120	150	Aerospace alloys, superconductors	X
Tantalum	4400	260	650	Aerospace alloys, capacitors, chemical engineering	X
Tungsten	520	35	170	Lamp filaments, rocket nozzles, armor plate	X

^aThe **X**-flag means that the element is considered to be a “critical” material.

(c) Rare-earth elements. “Rare-earth” elements appear together in the periodic table in the Lanthanide group. They are not particularly rare, but they are particularly important in low-carbon technologies, particularly in magnets and batteries. All are classified as “critical.”

Element	Energy (MJ/kg)	CO _{2,eq} (kg/kg)	Water (L/kg)	Unique applications	Critical material flag ^a
Cerium	520	34	55	Catalytic converters, aluminum alloys	X
Dysprosium	1400	94	55	High-field magnets, lasers	X
Europium	21,000	1600	55	Displays, superconductors	X
Gadolinium	1300	88	55	X-ray and MRI scanners, displays	X
Lanthanum	270	18	55	Lenses	X
Neodymium	85	5	55	High-field magnets	X
Praseodymium	640	42	55	Superalloys, high-field magnets	X
Samarium	1200	78	55	High-field magnets, glass and glazes	X
Terbium	9200	1000	55	Lasers, high-field magnets, displays	X
Yttrium	1500	89	55	Lasers, displays	X

^aThe **X**-flag means that the element is considered to be a “critical” material.

B4. Embodied energy and carbon footprint for electronic components

Electronic components—integrated circuits, surface-mount devices, displays, batteries, and the like—are now an integral part of most appliances. They don’t weigh much, but they are energy intensive and have a high carbon footprint. The data listed here are approximate, but give an indication.

Product			Energy (MJ)	Carbon, CO _{2,eq} (kg)
Systems	Per kg	Desktop computer (without screen)	410	24
		Laptop computer	940	190
		LCD panel (liquid crystal display)	240	18
		Printer (laser jet), black and white or color	190	15
		Small (hand-held) electronic devices	2800	210
Subsystems	Per kg	CD-ROM/DVD-ROM drive (laptop or desktop)	350	20
		Fan	250	12
		Hard disk drive (laptop or desktop)	440	25
		Hard disk/CD-ROM/DVD-ROM drive	460	26
		Integrated circuit, logic or memory type	1300	710
		Integrated circuit (large)	8000	60
		Integrated circuit (small)	1800	130
		Keyboard	370	22
		Optical mouse, with cable	740	42
		Power supply unit	450	34
		Printed circuit board assembly	130	9.7
		Printed wiring board (for desktop)	2800	160
		Printed wiring board (for laptop)	4600	270
		Toner module (laser jet)	240	11
		Transformer	86	6.4
Components	Per kg	Cable	91	6.8
		Capacitor	1400	78
		Diodes and LEDs	4600	230
		Inductor	1100	59

Product		Energy (MJ)	Carbon, CO ₂ .eq (kg)		
		Plug, inlet, and outlet	120	52	
		Resistor	1000	56	
		Semiconductor diodes, LEDs	3000	220	
		Transistor	2900	140	
	Per unit	Plug, inlet, and outlet	11	0.7	
	Per m	Cable	5–10	0.2–0.5	
	Power sources	Per kg	Alkaline AA cell	42	3.1
			Lead-acid battery (for cars)	19	1.4
			Li-ion AA cell battery	200	15
			Li-ion battery (for scooters)	320	24
Li-ion, rechargeable battery (laptop)			90	10	
Ni–Cd AA cell battery			140	11	
Ni–Cd C cell battery			69	5.2	
Ni–Cd rechargeable battery			240	18	
NiMH, rechargeable battery (laptop)			920	63	
Per unit		Alkaline AA cell battery	1	0.1	
		Li-ion AA cell battery	3	0.2	
		Ni–Cd AA battery	3	0.2	
		Ni–Cd C cell battery	5	0.4	
Materials	Per kg	Monocrystal silicon, electronics	5000	370	
		Monocrystal silicon, photovoltaics	1700	130	
		Solder (lead based)	220	16	
		Solder (lead free)	370	28	
	Per m ²	Monocrystal–Si wafer, electronics	6017	305	
		Mono crystal–Si wafer, photovoltaics	2804	129	
		Polysilicon wafer	2000	90	

B5. Embodied energies and carbon footprints of building materials

Domestic and commercial buildings consume materials on an enormous scale. The structure uses the most; the envelope enclosing and insulating the structure comes second, the services third, and the interior finishing and decoration require the least, but all are large. The materials of construction are a little more specialized than those of general engineering; many are not really “materials” but are, more properly, “systems.”

	Density (kg/m ³)	Embodied energy		Carbon footprint	
		(MJ/kg)	(MJ/m ³)	(kg/kg)	(kg/m ³)
Primary structure					
Aggregate	1500	0.10	150	0.006	9
Brick, common	2100	2.8	5880	0.22	462
Concrete, 30 MPa	2450	1.3	3180	0.095	233
Concrete block	2500	0.94	2350	0.061	151
Concrete, high-volume fly ash	2010	1.14	2290	0.068	137
Concrete, precast	1390	2.00	2780	0.12	167
Concrete, reinforced (8 wt% steel)	2910	2.49	7250	0.21	611
Concrete, standard	2.390	1.14	2700	0.1	239
Soil cement (rammed earth)	1950	0.42	819	0.03	55
Steel, virgin	7850	27	212,000	1.8	14,100
Steel, 100% recycled	7850	7.3	57,300	0.57	4470
Steel, typical 42% recycled content	7850	18.7	147,000	1.23	9660
Straw bale	125	0.22	27	−0.99	−12
Timber, structural	550	7.3	1380	0.42	230
Enclosure					
Aluminum, virgin	2700	210	567,000	12	324,000
Aluminum, 43% recycled content	2700	131	354,000	7.7	220,800
Duck (cellulose-based fabric)	980	72	7060	4.5	4.230

	Density (kg/m ³)	Embodied energy		Carbon footprint	
		(MJ/kg)	(MJ/m ³)	(kg/kg)	(kg/m ³)
GFRP (sheet molding compound)	1900	115	220,000	8.1	1540
Glass	2400	15.9	37,550	0.76	1820
Gypsum wallboard	1000	6.0	6000	0.33	3300
Insulation, cellulose	40	3.3	112	0.1	4.0
Insulation, fiberglass	32	30.3	970	2.1	67
Insulation, mineral wool	9.5	14.6	139	1.0	9.5
Insulation, polystyrene	32	117	3700	4.2	40
Insulation, vermiculite	101	25	2530	1.37	138
Particleboard	550	8.0	4400	0.6	330
Plywood	600	10.4	5720	0.8	480
Sealants: silicone, neoprene, epoxy	1100	120	132,000	7.5	8250
Shingles, asphalt	540	9.0	4930	0.6	329
Services					
Brass, fittings	8100	54	437,000	3.5	28,400
Copper: piping, cladding	8940	60	536,000	3.7	33,100
Lead: cladding, piping	11,300	27	305,000	1.9	21,500
Poly(vinyl chloride): piping	1370	68	93,200	3.1	2600
Steel, galvanized	7845	35	275,000	2.1	16,500
Zinc, cladding	7140	46	328,000	3.3	23,600
Interior					
Carpet, synthetic	570	148	84,900	8.8	
Hardwood	980	8.0		0.47	
Leather	922	107		4.29	
Linoleum	1300	116	150,930	5.8	
Paint	1260	93	117,500	4.6	
Tiles, terracotta	2290	3.0		0.22	
Particleboard, chipboard	550	8.0	4400	0.6	
Softwood	550	7.3	1380	0.42	230

B6. Process energy and carbon footprint of processes

Metals, typically, are shaped by casting, rolling, or forging. Polymers are molded or extruded. Ceramics are shaped by powder methods, composites are created by molding or layup methods. The primary processing energy is the energy in MJ/kg required to do this. The associated CO₂ footprint is evaluated by direct measurement or by calculating it from the energy use and fuel type. Secondary processes—machining, joining, and surface treatment—have associated energy and carbon consequences. The data listed here are indications of the relative magnitudes of energy and carbon. The CES EduPack (2019) lists processing data for individual materials.

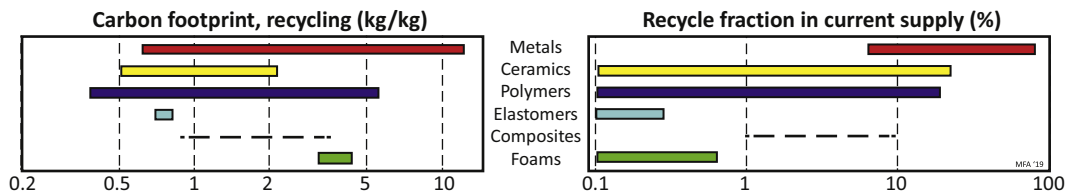
Primary processes		Energy (MJ/kg)	Carbon, CO _{2,eq} (kg/kg)
Metals	Casting	9	0.65
	Roll forming, forging	4.5	0.3
	Extrusion	14	0.9
	Wire drawing	35	2.3
	Metal powder forming	25	2.3
	Vapor phase methods	500	33
Polymers	Extrusion	6.5	0.42
	Molding	20.5	1.3
Ceramics, glasses	Ceramic powder form	50	3.3
	Glass molding	9.5	0.62
Composites	Compression molding	5.5	0.36
	Spray/layup	13	0.85
	Filament winding	7.5	0.48
	Autoclave molding	35	2.3
Secondary processes		Energy (MJ/kg removed)	Carbon, CO _{2,eq} (kg/kg removed)
Machining	Heavy (rough)	1.3	0.085
	Finishing (light)	6.5	0.42
	Grinding	55	3.6
	Water jet, EDM, laser	240	15
Secondary processes	Variants	Typical range of energies	Typical range of Carbon, CO _{2,eq}
Welding	Gas welding	1.9 MJ/m	0.12 kg/m
	Electric welding	2.6 MJ/m	0.17 kg/m

Secondary processes	Variants	Typical range of energies	Typical range of Carbon, CO _{2,eq}
Joining fasteners	Fasteners, small	0.03 MJ/fastener	0.002 kg/fastener
	Fasteners, large	0.075 MJ/fastener	0.005 kg/fastener
Adhesives	Adhesives, cold	10.5 MJ/m ²	0.68 kg/m ²
	Adhesives, heat-curing	29 MJ/m ²	2.0 kg/m ²
Painting	Painting	55	4.0
Surface Treatment	Baked coatings	65	4.2
	Powder coating	77	5.0
Plating	Electroplating	90	5.8

Data sources are listed under the table headings in Chapter 6, Section 6.8, "Further reading."

B7. Recycle fraction, recycle energy, and recycle carbon footprint

Not all the embodied energy of a material is really “embodied,” but some is. This retained energy means that the energy to recycle a material is usually less than that required for its first production. The recycled fraction in current supply (column 3) is an indicator of the viability of recycling. Columns 4 and 5 give an indication of the associated energy demand and CO₂ release. Products may require shredding before recycling. The energy penalty for shredding is 0.15–0.3 MJ/kg. The carbon footprint is 0.001–0.002 kg CO₂/kg.



Metals		Recycle fraction (%)	R-energy (MJ/kg)	R-carbon CO _{2,eq} (kg/kg)
Ferrous metals	Cast iron	69	8.5	0.67
	High-carbon steel	42	8.5	0.67
	Low-alloy steel	42	9	0.65
	Low-carbon steel	42	8.1	0.64
	Medium-carbon steel	42	8.5	0.67
	Stainless steel	37	16	1.2
Nonferrous metals	Aluminum alloys	43	33	2.6
	Copper alloys	43	13	1.1
	Lead alloys	72	8.6	0.67
	Magnesium alloys	39	49	3.8
	Nickel alloys	24	37	2.9
	Silver	6	150	12
	Tin	6	38	2.9
	Titanium alloys	23	81	6.4
	Tungsten alloys	36	75	5.9
	Zinc alloys	22	12	0.97

Metals		Recycle fraction (%)	R-energy (MJ/kg)	R-carbon CO _{2,eq} (kg/kg)
Ceramics		Recycle fraction (%)	R-energy (MJ/kg)	R-carbon CO _{2,eq} (kg/kg)
Glasses	Borosilicate glass (Pyrex)	24	24	1.2
	Silica glass	25	32	1.6
	Soda-lime glass	24	8.7	0.53
Technical ceramics	Alumina	0.7	36	2
	Aluminum nitride	0.1	—	—
	Silicon	0.71	—	—
	Silicon carbide	0.1	—	—
	Tungsten carbides	31	—	—
	Zirconia	0.1	—	—
Nontechnical ceramics	Brick	17	—	—
	Cement	1.2	—	—
	Concrete	13	0.8	0.07
	Stone	1.4	—	—
Polymers		Recycle fraction (%)	R-energy (MJ/kg)	R-carbon CO _{2,eq} (kg/kg)
Elastomers	Butyl rubber (IIR)	2.8	—	—
	Ethylene vinyl acetate (EVA)	0.1	27	0.72
	Natural rubber	0.1	—	—
	Polychloroprene (neoprene)	1.4	—	—
	Polyisoprene	0.1	—	—
	Polyurethane	0.1	—	—
	Silicone elastomers	0.1	—	—
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	4	32	1.2
	Cellulose polymers (CA)	0.7	30	1.2
	Ionomer (I)	0.1	38	1.9

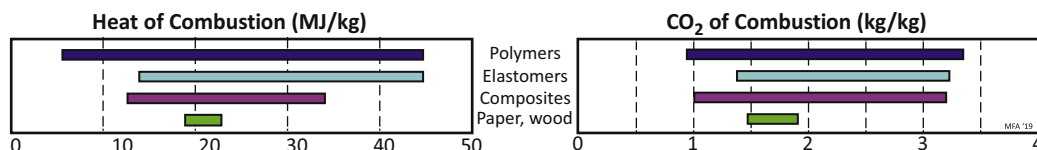
(Continued)

Polymers		Recycle fraction (%)	R-energy (MJ/kg)	R-carbon CO _{2,eq} (kg/kg)
	Polyamides (nylons, PA)	0.71	43	3
	Polycarbonate (PC)	0.7	37	2.4
	Polyether ether ketone (PEEK)	1.4	100	5.7
	Polyethylene (PE)	8.4	27	0.94
	Polyethylene terephthalate (PET)	21	28	1.5
	Poly lactide (PLA)	0.33	18	0.95
	Polymethyl methacrylate (PMMA)	0.7	38	2.2
	Polyoxymethylene (acetal, POM)	0.1	36	1.8
	Polypropylene (PP)	5.5	23	0.99
	Polystyrene (PS)	6	29	1.3
	Polytetrafluoroethylene (Teflon, PTFE)	0.7	39	1.9
	Polyurethane (tpPUR)	0.1	28	1.1
	Poly(vinyl chloride) (tpPVC)	1.5	23	1.1
	Thermoplastic starch (TPS)	0.1	8.6	0.37
Thermosets	Epoxies	0.7	—	—
	Phenolics	0.7	—	—
	Polyester	0.1	—	—
Foams	Flexible polymer foam	8.4	49	3.9
	Rigid polymer foam	0.1	—	—
Composites		Recycle fraction (%)	R-energy (MJ/kg)	R-carbon CO _{2,eq} (kg/kg)
Isotropic	CFRP, epoxy matrix	0.1	—	—
	GFRP, epoxy matrix	0.1	—	—
Natural		Recycle fraction (%)	R-energy (MJ/kg)	R-carbon CO _{2,eq} (kg/kg)
Wood-based	Paper and cardboard	72	22	0.7
	Softwood	9	—	—
	Hardwood	9	—	—

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

B8. Heat of combustion and combustion CO₂

Combustion releases heat and CO₂. Some of the heat can be recovered and used as an energy source.



Polymers		Heat of combustion (MJ/kg)	CO ₂ of combustion (kg/kg)
Elastomers	Butyl rubber (IIR)	44	3.2
	Ethylene vinyl acetate (EVA)	40	2.9
	Natural rubber	44	3.2
	Polychloroprene (neoprene)	17	1.4
	Polyisoprene	44	3.2
	Polyurethane	22	2
	Silicone elastomers	14	1.3
Thermoplastics	Acrylonitrile butadiene styrene (ABS)	39	3.1
	Cellulose polymers (CA)	19	1.8
	Ionomer (I)	37	2.7
	Polyamides (nylons, PA)	31	2.3
	Polycarbonate (PC)	31	2.8
	Polyether ether ketone (PEEK)	31	2.9
	Polyethylene (PE)	45	3.1
	Polyethylene terephthalate (PET)	24	2.3
	Poly lactide (PLA)	19	1.8
	Polymethyl methacrylate (PMMA)	26	2.2
	Polyoxymethylene (acetal, POM)	16	1.5

(Continued)

	Polypropylene (PP)	45	3.1
	Polystyrene (PS)	41	3.4
	Polytetrafluoroethylene (Teflon, PTFE)	4.8	0.9
	Polyurethane (tpPUR)	22	2
	Poly(vinyl chloride) (tpPVC)	18	1.4
	Thermoplastic starch (TPS)	17	1.6
Thermosets	Epoxies	31	2.5
	Phenolics	32	2.9
	Polyester	29	2.6
Foams	Flexible polymer foam (MD)	45	3.1
	Rigid polymer foam (MD)	18	1.4
Composites		Heat of combustion (MJ/kg)	CO₂ of combustion (kg/kg)
Isotropic	CFRP, epoxy matrix	32	3.3
	GFRP, epoxy matrix	12	1.0
Natural		Heat of combustion (MJ/kg)	CO₂ of combustion (kg/kg)
Wood-based	Paper and cardboard	20	1.5
	Softwood	21	1.8
	Hardwood	20	1.7

CFRP, carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer.

B9. Transport: energy and carbon footprint (data sources are listed in Chapter 6)

(a) Freight transport

Class	Transport type and fuel	Energy (MJ/tonne · km ⁺)	Carbon footprint (kg CO _{2,eq} /tonne · km ⁺)
Shipping	Very large container ship (20,000 TEU), diesel	0.04	0.003
	Oil tanker (100,000 tonnes), diesel	0.08	0.006
	Bulk carrier (25,000 tonnes), diesel	0.11	0.008
	Ocean shipping (10,000 tonnes), diesel	0.18	0.014
	Coastal shipping, diesel	0.27	0.021
	Barge, diesel	0.4	0.031
Rail	Rail freight, electric	0.22	0.016
	Rail freight, diesel	0.35	0.027
Road: truck	55-tonne (8-axle) truck, diesel	0.71	0.055
	40-tonne (6-axle) truck, diesel	0.82	0.063
	32-tonne (4-axle) truck, diesel	0.94	0.072
	26-tonne (3-axle) truck, diesel	1.1	0.085
	14-tonne (2-axle) truck, diesel	1.5	0.12
	Light goods vehicle, diesel	2.2	0.17
Road: car	Family car, diesel	1.7	0.13
	Family car, gasoline	2.6	0.18
	Family car, liquid propane gas	2.6	0.13
	Family car, hybrid gasoline—electric	1.4	0.10
	Super sports car and SUV, gasoline	3.4	0.24
Air	Long-haul aircraft, kerosene (747)	6.5	0.54
	Short-haul aircraft, kerosene	13	1.1
Class	Transport type and fuel	Energy (MJ/min)	Carbon footprint (kg CO _{2,eq} /min)
Air	Helicopter (Eurocopter AS 350), kerosene	22	1.6

(Continued)

(b) Personal transport

Class	Transport type and fuel	Energy (MJ/passenger • km^a)	Carbon footprint (kg CO_{2,eq}/passenger • km^a)
Car	Small car, one passenger, petrol	1.8	0.13
	Small car, four passengers, petrol	0.6	0.04
	Large car, one passenger, diesel	3.3	0.22
	Large car, four passengers, diesel	1.0	0.064
Train	Amtrak, diesel	2.8	0.19
	EU TGV, electric	0.64	0.045
Bus	Greyhound, diesel	1.6	0.11
	Inner-city bus, diesel	2.1	0.13
Plane	Short haul, kerosene	3.9	0.28
	Long haul, kerosene	2.7	0.19
Ship	Cruise liner (QEII), diesel	4.5	0.27
	Ferry (Dover to Calais), diesel	3.0	0.2

^a1 metric tonne = 1.1 US ton; 1 ton • mile = 1.46 tonne • km

B10. Energy: fuels and carbon-adjustment factors

(a) The energy density and carbon footprint of fossil fuels.

Reading across the table, there is the fuel type, the oil equivalent (OE—the kilograms of crude oil with the same energy content as 1 kg of the fuel), the energy content per unit volume and per unit weight, and the CO₂ release per unit liter, per kilogram, and per megajoule. SI units (kg, MJ, etc.) are used here. Conversion factors to other systems (lb, Btu, etc.) can be found at the end of the book.

Fuel type	kg OE ^a	MJ/L	MJ/kg	CO ₂ , kg/L	CO ₂ , kg/kg	CO ₂ , kg/MJ
Coal, lignite	0.45	—	18–22	—	1.6	0.080
Coal, anthracite	0.72	—	30–34	—	2.9	0.088
Crude oil	1.0	38	44	3.1	3.0	0.070
Diesel	1.0	38	44	3.1	3.2	0.071
Gasoline	1.05	35	45	2.9	2.9	0.065
Kerosene	1.0	35	46	3.0	3.0	0.068
Ethanol	0.71	23	31	2.8	2.6	0.083
LNG (LPG)	1.2	25	55	3.03	3.0	0.055
Hydrogen	2.7	8.5	120	0	0	0

LNG, *liquid natural gas*; LPG, *liquid propane gas*.

^aKilograms oil equivalent (the kilograms of oil with the same energy content).

(b) Adjustment factors for carbon footprint for alternative fuel and electricity energy mixes.

The carbon footprint of materials depends on the energy mix in the country in which it was produced. Energy mix (Appendix B, Table B11) varies from country to country. Ideally, we would like directly measured values for carbon footprints that are country specific, but such data don't exist. If we assume that the *energy* to make a material is country independent, we can correct the *carbon footprint* to match the country-specific energy mix. We take oil as the norm for hydrocarbons and electricity supply from a gas-fired power station with 38% efficiency as the norm for electrical power. Table B10(b) lists the correction factor to be applied to carbon footprint from fuels and electrical energy use for 100% conversion to the listed source. The correction factor for actual energy mixes can then be found by linear interpolation.

Hydrocarbon fuel source	Correction factor for carbon footprint ^a	Electricity energy source	Correction factor for carbon footprint
100% oil (diesel)	1	75% oil/gas (EU average)	1
100% kerosene	0.96	100% coal	2
100% gasoline	0.92	100% nuclear	0.06
100% natural gas	0.77	100% solar photovoltaic	0.2
100% bio-diesel	0	100% wind	0.08
100% bio-ethanol	0	100% hydro	0.06
100% hydrogen	0–0.1	100% geothermal	0.05

^aThe correction factors for hydrocarbon-based power are the ratios of CO₂/MJ of fuel to that of oil, using data from Table B10(a)

B11. Energy mix by country

Energy mix and MJ oil per kilowatt-hour and CO₂ per kilowatt-hour* by country.

Today most electricity is generated by burning fossil fuels, but there is now a transition to nuclear and renewable sources. The *energy mix* in the electricity supply of a country is the proportional contribution of each source to the total.

Country	Fossil fuel		Nuclear	Renewables	MJ _{oe} ^b /kWh ^d	CO ₂ ^c , kg/kWh ^d
	Proportion	Efficiency ^a	Proportion	Proportion		
World average	0.67	0.36	0.15	0.19	7.85	0.47
Europe	0.53	0.33	0.27	0.20	7.45	0.41
Former USSR	0.65	0.33	0.18	0.17	8.35	0.50
North America	0.66	0.33	0.18	0.16	8.42	0.51
Latin America	0.27	0.33	0.02	0.71	5.58	0.21
Asia	0.80	0.33	0.04	0.17	9.43	0.62
Pacific	0.65	0.33	0.25	0.10	8.35	0.50
Middle East	0.97	0.33	0.00	0.03	10.7	0.75
Australia	0.92	0.33	0.00	0.08	10.3	0.71
Austria	0.33	0.33	0.00	0.67	6.0	0.25
Belgium	0.39	0.33	0.54	0.06	6.5	0.29
Brazil	0.10	0.33	0.03	0.87	4.3	0.08
Canada	0.24	0.38	0.16	0.60	5.0	0.16
China	0.83	0.33	0.02	0.15	9.7	0.64
Czech Republic	0.64	0.32	0.31	0.05	8.5	0.51
Denmark	0.78	0.33	0.00	0.22	9.3	0.60
Finland	0.44	0.33	0.28	0.28	6.8	0.34
France	0.10	0.40	0.78	0.12	4.1	0.06
Germany	0.61	0.38	0.26	0.13	7.2	0.41
Greece	0.86	0.37	0.00	0.14	8.9	0.60
Hungary	0.58	0.33	0.38	0.05	7.8	0.45
Iceland	0.00	0.33	0.00	1.00	3.6	0.02
India	0.81	0.27	0.03	0.17	11.5	0.77
Ireland	0.90	0.33	0.00	0.10	10.1	0.69

(Continued)

Country	Fossil fuel		Nuclear	Renewables	MJ _{oe} ^b /kWh ^d	CO ₂ ^c , kg/kWh ^d
	Proportion	Efficiency ^a	Proportion	Proportion		
Italy	0.81	0.45	0.00	0.19	7.2	0.46
Japan	0.61	0.43	0.28	0.11	6.5	0.36
Korea	0.62	0.39	0.37	0.01	7.1	0.40
Mexico	0.80	0.38	0.04	0.16	8.3	0.54
Netherlands	0.87	0.44	0.04	0.10	7.6	0.50
New Zealand	0.35	0.33	0.00	0.65	6.2	0.27
Norway	0.01	0.33	0.00	0.99	3.6	0.01
Poland	0.96	0.36	0.00	0.04	9.8	0.68
Portugal	0.66	0.33	0.00	0.34	8.5	0.51
Russia	0.66	0.32	0.16	0.18	8.7	0.53
Slovak Republic	0.27	0.33	0.57	0.16	5.5	0.21
South Africa	0.94	0.37	0.04	0.02	9.3	0.65
Spain	0.60	0.39	0.20	0.20	7.0	0.40
Sweden	0.03	0.33	0.47	0.50	3.8	0.02
Switzerland	0.02	0.33	0.43	0.55	3.6	0.01
Turkey	0.75	0.43	0.00	0.25	7.2	0.44
United Kingdom	0.75	0.43	0.19	0.06	7.2	0.45
United States	0.71	0.36	0.19	0.10	8.1	0.50

^aConversion efficiency of fossil fuel to electricity.

^bMJ_{oe} of fossil fuel (oil equivalent) used in energy mix per kWh of delivered electricity from all sources.

^cCO₂ release per kWh of delivered electricity from all sources.

^d1 kWh is 3.6 MJ_{electric}.

B12. Efficiency factors for energy conversion

Energy takes many forms: chemical (as in oil), mechanical (potential, kinetic), electrical, magnetic, thermal, and electromagnetic radiation. When one form of energy is converted to another, there are usually losses, meaning that some of the energy is “lost” as low-grade heat with no useful purpose. The table lists approximate conversion efficiencies.

Energy conversion path	Efficiency, direct conversion (%)	Efficiency relative to oil equivalence (%)	Associated carbon (kg CO ₂ per useful MJ)
Gas to electric	37–40	37–40	0.18
Oil to electric	36–38	36–38	0.2
Coal to electric	33–35	33–35	0.22
Biomass to electric	23–26	23–26	0
Hydro to electric	75–85	75–85	0
Nuclear to electric	32–34	32–34	0
Fossil fuel to heat, enclosed system	100	100	0.07
Fossil fuel to heat, vented system	65–75	65–75	0.10
Biomass to heat, vented system	33–35	33–35	0
Oil to mechanical, diesel engine	20–22	19–21	0.17
Oil to mechanical, petrol engine	13–15	12–14	0.15
Oil to mechanical, kerosene gas turbine	27–29	25–27	0.15
Electric to thermal	100	37–40	0.20
Electric to mechanical (electric motors)	80–93	30–32	0.23
Electric to chemical (lead-acid battery)	80–85	29–32	0.24
Electric to chemical (advanced battery)	85–90	31–33	0.23
Electric to electromagnetic radiation (incandescent lamp)	12–15	4–6	1.17
Electric to electromagnetic radiation (LED)	80–85	29–32	0.23
Light to electric (solar cell)	10–22	—	0

Index

Note: Page numbers followed by “f” indicate figures and “t” indicate tables.

A

A-rated washing machine (eco-audit case study), 175–176
 Abundance risk, 301
 Acidification, 48–50
 Adaptability, 72
 Adobe, 288
 Agave (*Agave sisalana*), 290
 Agenda for Sustainable Development (2030), 341–343
 Aggregated measures, 51
 Agreements, international, 90–92
 Alloying, 4
 Aluminum and aluminum alloys
 embodied energy, 110–111
 exponential growth of consumption, 33
 Animal-derived fibers, 291
 Animal-derived materials, 289–290
 Annual world production (consumption), 25, 26f
 and reserves for materials, 405
 Asbestos, 288
 Asphalt, world consumption of, 25, 26f
 Auto bumpers (eco-audit case study), 182–183
 Azurite, 2–4

B

Bakelite, 5
 Balance, 317–319
 Bamboos, 289
 Bar charts. *See also* Property charts
 Battery Directive, 95
 Bessemer process, 4
 Bill of materials for eco-audits, 153
 Bio-based composites, 279–284, 291

Bio-based materials, 268
 Bio-composites, 279–281
 Bio-fuel, carbon footprint of products using, 136b–137b
 Bio-plastics, 274
 Bio-polyethylene, 274
 Bio-polypropylene, 274
 Biopolymers, 274–276
 Blow-molding, 123–124
Boehmeria nivea. *See* Ramie (*Boehmeria nivea*)
 Bonded board, 291
 Bone, 289–290
Borassus. *See* Palmyra palm (*Borassus*)
 Brick
 annual world consumption (production), 25, 26f
 fired and unfired, 288
 Bronze, 4
 Bronze Age, 2
 Brundtland Report (1987), 341–343, 342f
 Bubble charts. *See also* Property charts
 Buildings
 initial and recurring embodied energy of, 238–240
 structural materials for, 236–238
 Buildings and construction
 materials consumption, 25, 26f

C

CAFE. *See* Corporate Average Fuel Economy (CAFE)
Cannabis sativa, 290
 Car bumpers, 182
 Carbon
 carbon-adjustment factors, 425
 carbon-to-energy ratios, 113
 cycle, 317
 equivalent, 110

Carbon dioxide (CO₂), 60–61
 impact assessment factor, 48–50, 49t
 Carbon fiber
 annual world consumption (production), 25, 26f
 Carbon footprint, 108, 110
 of building materials, 414
 using data for, 134b–136b
 for electronic components, 412
 electronics, 122b
 for engineering materials, 407
 fossil fuels, 128
 of processes, 416
 of products using bio-fuel, 136b–137b
 in property charts, 112
 in secondary processes, 124–125
 of structure and enclosure, 123b
 use-phase energy and, 128–129, 129b
 Carbon monoxide (CO), 60–61
 impact assessment factor, 48–50, 49t
 Carbon-fiber-reinforced polymers (CFRP), 33, 182, 251–253
 Carbonated-water bottles, systematic eco-selection, 233–236
 Carrier bags (eco-audit case study), 170–172
 Cars, energy intensity of, 132t
 Cast iron, 4
 CD. *See* Climate declaration (CD)
 CES EduPack (2019) tool, 61
 Chip board, 291
 Circular materials economics, 315–316, 321–334
 ecological metaphor, 316–319
 resource husbandry, 319–321
 “Circularity” concept, 157–160, 316

- Classification of LCA results, 51
 Climate declaration (CD), 92
 Club of Rome, "Limits to Growth", 89t
 Club of Rome, 10–11
 Coal, 116
 annual world consumption (production), 25, 26f
 Cob, 291
 Coffee maker (eco-audit case study), 173–175
 Coir, 290
 Combustion (for heat recovery), 67. *See also* End-of-life options for products
 CO₂, 421
 Command and control approach, 88–90
 Commercial water usage, 29–30
 Commodity price, 25
 Composites, 5
 Computer-aided eco-auditing, 160
 Computer-aided materials selection, 217–218
 Computer-assisted audits, 183–187
 Concrete
 annual world consumption (production), 25, 26f
 combustion (for heat recovery), 67
 Conflict risk, 306–307
 Constraints in material selection, 196–204
 Conventions, international, 90–92
 Copper, 2–4, 24
Corchorus, 290
 Cork, 289
 board, 291
 Corporate Average Fuel Economy (CAFE), 96, 97f
 Corporate social responsibility, 306–307, 356–360
 changing expectations, 307–308
 Cotton, 290
 Cradle-to-gate studies, 50
 Crash barriers (example), 250–253
 Critical
 materials, 296–299
 mineral, 296–299
 Criticality, 296
 Cumulative production, calculating, 33
- D**
 Data life, 133
 Daub, 291
 Density, material, 374
 Dependence on certain materials, 2, 7–8
 nonrenewable materials, 7–10
 Deriving material indices, 220–223
 Design for the environment, 321
 Design process, materials life cycle, 42, 43f
 Desirability life, 67
 Dielectric constant, 394
 Digital chemistry, 6
 Digression, 115
 Dinitrous monoxide (N₂O)
 impact assessment factor, 48–50, 49t
 Documentation for material selection, 202
 Doubling-time (t_D), 31–34
 Dow Jones Sustainability World Index, 358
 "Drop-in" biopolymers, 274
 Ductility, 2–4
- E**
 E-LCA. *See* Environmental life-cycle assessment (E-LCA)
 Eco-audits, 56–57, 149–150
 assigning recycle credits, 156–157
 circularity, 157–160
 computer-aided, 160
 energy and carbon finger-prints of products, 150–153
 methods, 42
 output, 151f, 155
 overview, 149–150
 procedure, 153–155
 bill of materials, 153
 disposal, 155
 manufacturing, 153
 transportation, 153–154
 use phase, 154–155
 Eco-audits (case studies), 165
 A-rated washing machine, 175–176
 auto bumpers, 182–183
 carrier bags, 170–172
 coffee maker, 173–175
 family car, 183
 Eco-audits (case studies) (*Continued*)
 hair dryer, 183–187
 portable space heater, 178–181
 reusable and disposable cups, 166–170
 Ricoh Imagio MF6550 copier, 176–177
 wheelie bin, 166, 166f, 167t
 Eco-charts, use of, 212b. *See also* Property charts
 Eco-data, 403
 material eco-attributes, 108–129
 material property charts, 112
 precision of, 108
 Eco-design, exchange constants for, 216–217
 Eco-efficient design, material substitution for, 256–260
 Eco-indicators, 51
 steps in calculating, 51f
 Eco-properties of materials, 108–127
 Ecological footprint per capita, 345
 Ecological metaphor, 316–319
 Economic input–output LCA (EIO-LCA), 61
 Economical life, 67
 Economics
 geo-economic properties, 109
 legislative instruments, 88–90, 98–101
 of recycling, 74
 Efficiency
 factors for energy conversion, 429
 of shaping processes, 125b–126b
 Electrical resistivity, 394
 Electricity, 128
 Electronics, 122
 energy and carbon footprint, 122b
 Embodied energy, 66, 108, 110
 of building materials, 414
 for electronic components, 412
 for engineering materials, 407
 initial and recurring embodied energy of buildings, 238–240
 in property charts, 112
 structural materials for, 236–238
 Emissions, 44–45
 ISO 14025 standard, 92
 Kyoto Protocol (1987), 89t
 Kyoto Protocol (1997), 90

- Emissions (*Continued*)
 taxes, 98
 trading, 100
- End-of-life options for products,
 66, 68f
 list of, 67–70
 recycled materials as supply,
 77–78
- End-of-Life Vehicles (ELVs), 95
- Energy
 consumption of, 26
 eco-properties, 127–129
 electronics, 122b
 fuels and carbon-adjustment
 factors, 425
 kilns and cyclic heating
 (example), 245–248
 of recycling, 72–79
 refrigerators (example), 240
 saving energy by reducing weight,
 131b–133b
 sources, 26, 27f
 transport, 129–133
 units of measurement, 27
- Energy conversion, 28–29
 examples, 29f
- Energy mix
 adjusting for country-specific, 136
 by country, 427
- Energy mortgage, 110–111
- Energy Policy Conservation Act
 (1975), 96
- Energy-related products (ErP), 95
- Energy-using products (EuPs), 52,
 95
- Environmental cost, 44–45
 externalized, 44–45
 internalized, 44–45
- Environmental impact, 321
 design for the environment, 321
 landmark publications on
 pollution awareness, 89t
- Environmental life-cycle
 assessment (E-LCA), 353
- Environmental product
 declaration (EPD), 92, 176
- Environmentally responsible
 product rating (R_{erp}), 53
- EPA. *See* US Environmental
 Protection Agency (EPA)
- European legislation, 94
- Eutrophication, 48–50
- Exchange constants (materials
 selection), 214–215
- Explosive population growth, 13
- Exponential growth, 22
 of population, 13
- Export restriction risk, 305
- Externalized cost, 44–45
- F**
- Family car (eco-audit case study),
 183
- Fashion, refurbishment and, 69
- Feedstock, 111
- Fibers, 290
 annual world consumption
 (production), 25, 26f
 density and price, 398
 modulus and strength, 399–401
- Field stone, 288
- Flax, 290
- Forces for change, 335
- Fossil fuels, carbon footprint of,
 128
- Fracture toughness, 382
- Free variables in material
 selection, 196–204
- FTSE4Good Index, 358
- Fuel duty, 98
- Fuel economy standards, 95
- Fuels, 425
- Function in material selection,
 196–204
- Functional life, 66
- G**
- GaBi (2008) tool, 60
- Gate-to-gate studies, 46
- Geopolitical risk, 303
- Gizmos, recycle contribution of,
 79b
- Glass
 annual world consumption
 (production), 25, 26f
 temperature, 386
- Global Reporting Initiative (GRI),
 358
- Global warming potential, 48–50
- Goals of life-cycle assessment, 46
- Gold
 production and reserves, 48
- Gold, 2–4
- Good Country Index, 349–350
- Gossypium*, 290
- Green taxes, 98
- Greenhouse Gases, Regulated
 Emissions and Energy Use
 in Transportation Model
 (GREET) (2007) tool, 60–61
- Greenwashing, 357
- Gross domestic product (GDP),
 345–347
 per capita by region, 347f
- Growth, 317–319
 explosive growth, of population,
 13
 exponential, 2
 exponential, of population, 13
- H**
- Hair dryer (eco-audit case study),
 183–187
- Hardness, 378
- HDI. *See* UN Human
 Development Index (HDI)
- Heat of combustion, 421
- Heat recovery through
 combustion, 67
- Heating and cooling, 240–245
- Hematite (Fe_2O_3), 4
- Hemp, 290
- Hempcrete, 291
- Herfindahl–Hirschman Index
 (HHI), 303
- Hibiscus cannabinus*. *See* Kenaf
 (*Hibiscus cannabinus*)
- High-density polyethylene
 (HDPE), 166
- High-grade heat, 28–29
- History of materials, 2–7
- Horners' Guild, 4–5
- Human and social capital,
 354–356
- Human toxicity, 48–50
- Hydro-aluminum, 137b
- Hydrocarbon fuels
 annual world consumption
 (production), 25, 26f
- Hydrological cycle, 317
- Hydropower, 137b
- I**
- Ice, 288
- Impact, product of population,
 affluence and technology
 equation (IPAT equation),
 360–361

Impact assessment, 48–50
 Improved material extraction and yield, 324–325
 Incheon Report (2015), 89t
 Industrial design, 72
 Industrial ecology, 321
 Industrial revolutions, 7–10
 Information–communications–technologies (ICT), 329
 Initial and recurring embodied energy of buildings, 238–240
 Inorganic feedstock, 111
 Integrated Computational Materials Engineering (ICME), 6
 Interdependence of three capitals, 348
 Intergovernmental Panel on Climate Change (IPCC) Report of 2007, 11, 89t
 IPCC Fourth Assessment Report (2007), 89t
 Internalized cost, 44–45
 International Standards Organization (ISO), 45, 92
 ISO 14000 standard, 92
 ISO 14025 standard, 92
 Internet of things (IoT), 6
 Interpretation of life-cycle assessment, 50
 Inventory compilation of life-cycle assessment, 48
 Iron, 4

J

Jute, 290

K

Kenaf (*Hibiscus cannabinus*), 290
 Kilns and cyclic heating (example), 245–248
 Kyoto Protocol (1987), 89t
 Kyoto Protocol (1997), 90

L

Landfill, 66–67
 Landfill Directive, 94
 Landfill tax, 98
 Landmark publications on pollution awareness, 89t
 LCA Calculator (2011) tool, 61

Legal life, 67
 Legislation, 88, 304
 burden, 101–102
 economic instruments, 88–90, 98–101
 environmental awareness, 88–90
 international, 90–92
 national, 92–98
 Life cycle. *See* Materials life cycle
 Life-cycle assessment (LCA), 41–42, 44–45, 52f, 92, 150, 165
 details and difficulties, 45–52
 goals of, 46
 impact assessment, 48–50
 interpretation of, 50
 inventory compilation of, 48
 output of, 50, 50f
 precision of, 50
 scope of, 46
 software for, 60–61
 streamlined LCA, 52–55, 53f
 Life-cycle costing, 353–356
 Lifetime of power system, 404
 Lightweight structures (material selection case study), 253–256
 Lime, 288
 Linoleum, 291
 Linseed plant (*Linum usitatissimum*), 290
 Liquid propane gas (LPG), 178–180
 Low-grade heat, 28–29
 Luster, 6

M

Machining-process energies, 124–125
 Magnesium and magnesium alloys, 4
 embodied energy, 113–114
 Malachite, 2–4
 Malthus, Thomas, 11–13
 Manufactured and financial capital, 345–347, 353–356
 Market forces, 10
 Market need, 42
 Mass, minimizing, 196
 Material consumption, 324
 energy consumption, 26
 exponential growth and doubling times, 31–34
 water consumption, 29–30

Material dependence, 2, 7–8
 nonrenewable materials, 7–10
 Material efficiency, 324
 Material extraction efficiencies, 117–119
 Material Genome Initiative (MGI), 6
 Material indices, 198–199
 deriving, 220–223
 for scaling, 202
 shells (example), 255
 Material Input per Service Unit tool (MIPS tool), 61
 Material intensity, 61
 Material names and applications, 370
 Material production, 114, 324
 Material property charts, 204–209. *See also* Property charts
 Material property data, 369
 Material substitution
 for eco-efficient design, 256–260
 weight savings, 259b–260b
 Material[s]
 of architecture and construction, 123
 brief history of, 2–7
 eco-properties, 108–123
 and environment, 10–15
 supply chain
 recycling and, 77–78
 timeline, 3f, 6
 Materials life cycle, 41–42
 design process, 42, 43f
 idea of, 43–45
 life-cycle assessment, 41–42
 sketch of, 43, 44f
 Materials substitution
 volume savings by, 203b–204b
 weight savings by, 203b
 Materials timeline, 43f
 Matrix method, for LCAs, 53, 55f
 Meadow board, 291
 Measurement units
 in LCA inventory compilation, 48
 Mechanical properties of material selection, 269
 Melting temperature, 386
 Metal crash barriers, 250–253

- Metals
 average concentration, in earth's crust, 23f
 average concentration, in earth's oceans, 24f
 recycling, 73
 Methane (CH₄), 60–61
 impact assessment factor, 48–50, 49t
 MF6550 digital copier (eco-audit case study), 176
 MGI. *See* Material Genome Initiative (MGI)
 Mineral fibers, 288
 Mineral foams, 288–289
 Mineral-based materials, 288
 Modulus–carbon footprint charts, 206
 Modulus-density chart, 204
 Monopoly of supply, 303
 Montreal Protocol (1987), 89t
 Montreal Protocol (1989), 90
- N**
 Nanoscience, 6
 Napoleonic Wars, 6
 National legislation, 92–98
 Natural capital, 345, 353
 Natural fibers, 276–279, 277f
 annual world consumption (production), 25, 26f
 material profile for
 coir, 279–281
 flax, 279–281
 hemp, 279–281
 jute, 279–281
 kenaf, 279–281
 sisal, 279–281
 Natural materials, 268–273, 288–291
 Natural resources, 10–11
 Natural rubber, 269
 Natural vegetable fibers, 290
 Need statement, 42
 Net human capital, 345
 Net manufactured capital, 345
 Net natural capital, 345
 New (primary) scrap, 74
 Nitrates, 48–50
 Nitrogen cycle, 317
 Nitrogen oxide (NO_x), 60–61
 Nitrous oxide (N₂O), 60–61
- Non-metals
 average concentration, in earth's crust, 23f
 average concentration, in earth's oceans, 24f
 Nongovernmental organization (NGO), 349–350
 Nonrenewable materials,
 dependence on, 7–10
 Normalization of LCA results, 51
 Nuclear energy, 27
- O**
 Oak, material profiles for, 289
 Objective function, 220–221
 Objectives in material selection, 196–204
 Offsetting (emission trading), 101
 Oil
 annual world consumption (production), 25, 26f
 equivalents for electronic power, 128
 Oil equivalence of electric power, 154–155
 Oil prices, increase in, 96
 Old (secondary) scrap, 74
 Ore grade, 23
 Organisation for Economic Co-operation and Development (OECD), 349
 Output of life-cycle assessment, 50, 50f
 Ozone depletion, 48–50
- P**
 Packaging, 70–72
 need, 70
 tamper-proof, 70–71
 Palm fiber, 290
 Palms, 289
 Palmyra palm (*Borassus*), 290
 Paper bags, 170
 Paris Agreement (2015), 89t, 90–91
 Particle board, 291
 PAS2050 standard, 92
 Passive solar heating (material selection), 241–245
 PE. *See* Polyethylene (PE)
 Peanut husk board, 291
 Penalty functions (materials selection), 214, 216b–217b
 refrigerators (example), 240
 Per unit of function, 230–233
 Perception, refurbishment and, 295
 Permits, 100
 Permits for emissions, 100
 Physical life, 66
 PLA. *See* Polylactide (PLA)
 “Planet, profit, and people” (three P’s), 344
 Plant life, 116
 Platinum
 production and reserves, 48
 Plywood, 291
 Polluter pays principle, 91
 Pollution control and prevention, 321
 Poly(vinyl chloride), 5
 annual world consumption (production), 25, 26f
 Polyethylene (PE), 5
 annual world consumption (production), 25, 26f
 Polyethylene terephthalate (PET), 110–111, 153, 230, 274
 annual world consumption (production), 25, 26f
 Polyhydroxyalkanoate (PHA), 274
 Polylactide (PLA), 234, 274
 Polymers, 5
 recycling, 73
 Polypropylene, 5
 annual world consumption (production), 25, 26f
 Polystyrene
 annual world consumption (production), 25, 26f
 cups, 167
 Polyurethane, 5
 Portable space heater (eco-audit case study), 178–181
 Precautionary principle (WCED report), 91
 Precious metals, 120–121
 in engineering structures, 121b
 Precious metals, 410–411
 Precision of life-cycle assessment, 50
 Precision of measurement, 108
 Price, 374
 Price inelasticity, 301
 Price volatility risk, 301
 Primary (new) scrap, 74

- Principle 1 (Stockholm Convention), 91
 - Principle 2 (Rio Declaration), 91
 - Process chains, 126b
 - Process energy, 416
 - Product Liability Directive (1985), 94
 - Product life, 66–67
 - end-of-life options, 66, 68f
 - list of, 67–70
 - recycled materials as supply, 77–78
 - Product life-cycle management system (PLM system), 102
 - Product packaging, 70–72
 - Production of materials
 - eco-properties of, 108–127
 - Property charts, 112
 - carbon footprint, 112
 - Protocols, international, 90–92
 - Pumice, 288–289
 - “Pure” polymers, 5
- Q**
- Quercus suber*, 289
- R**
- Rachel Carson, *Silent Spring* (1962), 89t
 - Ramie (*Boehmeria nivea*), 290
 - Rammed earth and adobe, 288
 - Ranking options in material selection, 198–199, 201b, 210
 - Rare earths, 410–411
 - Reconditioning, 69
 - Recycle carbon footprint, 418
 - Recycle energy, 418
 - Recycle fraction, 418
 - Recycling, 66, 68–69, 72–79, 327
 - assigning recycle credits, 156–157
 - contribution to supply, 77–78
 - economics of, 74
 - end of life and, 133–137
 - energy of, 73
 - gizmos and widgets, contribution of, 79b
 - of metals, 73
 - of polymers, 73
 - Reed, as building materials, 289
 - Reengineering and refurbishment, 66, 69
 - Refractive metals, 410–411
 - Refractory metals, 121–122
 - Refrigerators (example), 240
 - Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), 94
 - Regulatory risk, 304
 - Reinforced concrete, 5
 - Relative magnitudes of energies of material and processing, 126b–127b
 - Remanufacturing, design for, 326
 - Renewable materials, 268
 - Repair, 326
 - Repair, reuse, and recycling (three “Rs”), 315–316, 325
 - Resource base, 109
 - Resource Conservation and Recovery Act (RCRA), 93
 - Resource depletion, 48–50
 - Resource flow analysis, 110–111
 - Resource husbandry, 319–321
 - Resource inventory compilation, 48
 - Restoration, 69
 - Restriction of Hazardous Substances Directive, 95
 - Reusable and disposable cups (eco-audit case study), 166–170
 - Reuse, 66, 69
 - Rhodium
 - production and reserves, 48
 - Ricoh Imagio MF6550 copier (eco-audit case study), 176–177
 - Rio Declaration (1987), 89t
 - Risk management, 308
 - Rubber, 4–5
- S**
- Saltwater resources, 290
 - Satisfaction, refurbishment and, 69
 - Scope of life-cycle assessment, 46
 - Scrap, 74. *See also* Waste
 - primary, 74
 - recycling, 74
 - secondary, 74
 - Screening out options in material selection, 198, 201b, 209–210
 - Second World War, 6
 - Secondary (old) scrap, 74
 - Selection strategies for materials, 195–196
 - computer-aided, 217–218
 - criteria for, and property charts, 209–212
 - heating and cooling, 240–245
 - initial and recurring embodied energy of buildings, 238–240
 - kilns and cyclic heating (example), 245–248
 - passive solar heating, 241–245
 - per unit of function, 230–233
 - structural materials for buildings, 236–238
 - systematic eco-selection (carbonated-water bottles), 233–236
 - trade-off methods for resolving conflict, 213–217
 - Shaping-process energies, 124
 - Shells, 289–290
 - materials selection for, 255
 - Silicon, 5–6
 - Silks, 291
 - Silver, 2–4
 - SimaPro (2008) tool, 60
 - Single-use water bottle, 153
 - Sisal fiber, 290
 - Skin and hide, 289–290
 - Social adaptation, 329–330
 - Social and human capital, 347–348
 - Social impact categories, 355
 - Social life-cycle assessment (S-LCA), 354–356
 - goals and scope, 354
 - impact assessment, 356
 - interpretation and options for action, 356
 - inventory compilation, 355
 - Social protection spend, 349–350
 - Society of Environmental Toxicology and Chemistry (SETAC), 353
 - Software for LCA, 60–61
 - Solar energy, 241–242. *See also* Energy
 - Specific heat, 386
 - Standards, international, 90–92

Steel
 annual world consumption
 (production), 25, 26f
 steel-reinforced concrete, 5
 Stiffness, material indices for, 199
 Stock dynamics, 330–331
 Stockholm Convention (2001),
 89t
 Stockholm Earth Summit, The
 (1972), 89t
 Stone, 288
 Straw, 289
 Straw-bale construction, 291
 Straw-reinforced mud brick, 5
 Streamlined LCA, 42, 52–55, 53f
 Strength–carbon footprint charts,
 206
 Strength–density chart, 205
 Structural materials for buildings,
 236–238
 Subsidies, 98–101
 Sunflower seed board, 291
 Super alloys, 4
 Supply of materials, recycling and,
 77–78
 Supply-chain risk, 299–308
 Sustainability reporting (SR),
 356–360
 Sustainable development, 321,
 341
 corporate social responsibility,
 356–360
 at national level, 345–351
 principle, 91
 at product level, 351–356
 resources, consumption,
 population, affluence, and
 impact, 360–361
 sustainability reporting, 356–360
 and three capitals, 344–345
 Synthetic fibers, 276–279, 277f
 Systematic eco-selection
 (carbonated-water bottles),
 233–236
 Systematic trade-off strategies
 (materials selection), 213

T

Tamper-proof packaging, 70–71
 Taxes, 98–101
 TEAM (2008) tool, 60
 Technical life, 66

Tensile strength, 382
 Thermal conductivity of building
 materials, 390
 Thermal conductivity–thermal
 diffusivity chart, 207
 Thermal design, material indices
 for, 201
 Thermal diffusivity, 207–208
 Thermal expansion, 390
 Thermal lag time, 272–273
 Thermal management with
 renewable building
 materials, 273b
 Thermal mass of renewable
 building materials, 273b
 Thermal properties of material
 selection, 272
 Thermoplastic starch (TPS), 274
 Tin, 4
 Tooth, 289–290
 Toxic Substances Control Act, 93
 Trade-off methods for resolving
 conflict
 refrigerators (example), 240
 Trade-off methods for resolving
 conflict, 213–217
 Trading schemes, 98–101
 Transport, 248–250
 crash barriers (example), 250–253
 energy, 129–133
 energy and carbon footprint,
 423–424
 for light-weight structures
 (material selection example),
 253–256
 material substitution for eco-
 efficient design, 256–260
 Transport phase (products)
 exchange constants for trade-off,
 215t
 Treaties, international, 90–92
 Tree wood, 289

U

Ultra-efficient transport, 258–260
 UN Environment Programme
 (UNEP), 354
 UN Global Compact, 359b
 UN Human Development Index
 (HDI), 347–348

UN sustainable development
 goals for 2030, 341–343,
 343f
 UN World Commission on
 Environment and
 Development, The (WCED)
 report (1987), 89t
 Units of measurement
 in LCA inventory compilation, 48
 US Dodd–Frank Act, 306–308
 US Environmental Protection
 Agency (EPA), 93
 US EPA 35/50 Program, The, 93
 US EPA Code of Federal
 Regulation, 93
 US legislation, 93
 Use-phase energy, 128–129, 129b
 Utility function, 214–215

V

Value function, 214–215
 Vegetable fibers, 276–277
 Vegetable horsehair. *See* Palm
 fiber
 Vegetable-derived materials, 289
 Vermiculite, 288–289
 Virgin materials, 74
 Volatile organic compounds
 (VOCs), 93, 95
 Voluntary agreements, national,
 93
 Vulcanization, 4–5

W

Waste, 68–69
 fluctuating value, 76
 product packaging, 70–72
 Waste Electrical and Electronic
 Equipment (WEEE), 95
 Waste Framework Directive
 (WFD), 95
 Water, 29
 consumption, 29–30
 demand for engineering
 materials, 407
 usage, 115
 Water bottles, carbonated,
 233–236
 Wattle, 291
 Wave power, 101
 Wealth

Wealth (*Continued*)

- and commitment to common good, 349–350
- and environment, 350–351
- and social security, 349
- WEEE. *See* Waste Electrical and Electronic Equipment (WEEE)
- Weighting of LCA results, 51

Wheat board, 291

Wheelie bin (eco-audit case study), 166, 166f, 167t

Widgets, recycle contribution of, 79b

Wood, 4–5

annual world consumption (production), 25, 26f

Wools, 291

Y

- Yield, improved material extraction and, 324–325
- Yield strength, 378
- Young's modulus, 378

Z

Zinc, 33

Conversion of units: stress and pressure

To →	MPa	dyn/cm ²	lb/in ²	kgf/mm ²	bar	long ton/in ²
From ↓	Multiply by					
MPa	1	10 ⁷	1.45 × 10 ²	0.102	10	6.48 × 10 ⁻²
dyn/cm ²	10 ⁻⁷	1	1.45 × 10 ⁻⁵	1.02 × 10 ⁻⁸	10 ⁻⁶	6.48 × 10 ⁻⁹
lb/in ²	6.89 × 10 ⁻³	6.89 × 10 ⁴	1	7.03 × 10 ⁻⁴	6.89 × 10 ⁻²	4.46 × 10 ⁻⁴
kgf/mm ²	9.81	9.81 × 10 ⁷	1.42 × 10 ³	1	98.1	63.5 × 10 ⁻²
bar	0.10	10 ⁶	14.48	1.02 × 10 ⁻²	1	6.48 × 10 ⁻³
long ton/in ²	15.44	1.54 × 10 ⁸	2.24 × 10 ³	1.54	1.54 × 10 ²	1

Conversion of units: energy

To →	MJ	kWh	kcal	Btu	ft lbf	toe
From ↓	Multiply by					
MJ	1	0.278	239	948	0.738 × 10 ⁶	23.8 × 10 ⁻⁶
kWh	3.6	1	860	3.41 × 10 ³	2.66 × 10 ⁶	85.7 × 10 ⁻⁶
kcal	4.18 × 10 ⁻³	1.16 × 10 ⁻³	1	3.97	3.09 × 10 ³	99.5 × 10 ⁻⁹
Btu	1.06 × 10 ⁻³	0.293 × 10 ⁻³	0.252	1	0.778 × 10 ³	25.2 × 10 ⁻⁹
ft lbf	1.36 × 10 ⁻⁶	0.378 × 10 ⁻⁶	0.324 × 10 ⁻³	1.29 × 10 ⁻³	1	32.4 × 10 ⁻¹²
toe	41.9 × 10 ³	11.6 × 10 ³	10 × 10 ⁶	39.7 × 10 ⁶	30.8 × 10 ⁹	1

Btu, British thermal unit; ft lbf, foot-pound force; kcal, kilocalorie; kWh, kilowatt-hour; MJ, megajoules; toe, tonnes oil equivalent.

Conversion of units: power

To →	kW (kJ/s)	kcal/s	Hp	ft lbf/s	Btu/h
From ↓	Multiply by				
kW (kJ/s)	1	4.18	1.34	735	4.47 × 10 ⁴
kcal/s	0.239	1	0.321	176	1.07 × 10 ⁴
hp	0.746	3.12	1	550	3.35 × 10 ⁴
ft lbf/s	1.36 × 10 ⁻³	5.68 × 10 ⁻³	1.82 × 10 ⁻³	1	
Btu/h	2.24 × 10 ⁻⁵	9.33 × 10 ⁻⁵	3.0 × 10 ⁻⁵		1

Btu/h, British thermal units/hour; ft lb/s, foot-pounds/second; hp, horsepower; kcal/s, kilocalories per second; kW, kilowatt.

Physical constants in SI units

Physical constant	Value in SI units
Absolute zero temperature	−273.2°C
Acceleration due to gravity, <i>g</i>	9.807 m/s ²
Avogadro's number, <i>N</i> _A	6.022 × 10 ²³
Base of natural logarithms, <i>e</i>	2.718
Boltzmann's constant, <i>k</i>	1.381 × 10 ^{−23} J/K
Faraday's constant, <i>F</i>	9.648 × 10 ⁴ C/mol
Gas constant, <i>R</i>	8.314 J/mol/K
Permeability of vacuum, <i>μ</i> ₀	1.257 × 10 ^{−6} H/m
Permittivity of vacuum, <i>ε</i> ₀	8.854 × 10 ^{−12} F/m
Planck's constant, <i>h</i>	6.626 × 10 ^{−34} J/s
Velocity of light in vacuum, <i>c</i>	2.998 × 10 ⁸ m/s
Volume of perfect gas at standard temperature and pressure (STP)	22.41 × 10 ^{−3} m ³ /mol

Conversion of units, general

Quantity	Imperial unit	SI unit
Angle, <i>θ</i>	1 rad	57.30°
Density, <i>ρ</i>	1 lb/ft ³	16.03 kg/m ³
Diffusion coefficient, <i>D</i>	1 cm ³ /s	1.0 × 10 ^{−4} m ² /s
Energy, <i>U</i>	See inside back cover	
Force, <i>F</i>	1 kgf	9.807 N
	1 lbf	4.448 N
	1 dyne	1.0 × 10 ^{−5} N
Length, <i>ℓ</i>	1 ft	304.8 mm
	1 inch	25.40 mm
	1 Å	0.1 nm
Mass, <i>M</i>	1 tonne	1000 kg
	1 short ton	908 kg
	1 long ton	1107 kg
	1 lb mass	0.454 kg
Power, <i>P</i>	See inside back cover	
Stress, <i>σ</i>	See inside back cover	
Specific heat, <i>C</i> _p	1 cal/gal °C	4.188 kJ/kg °C
	Btu/lb °F	4.187 kg/kg °C
Stress intensity, <i>K</i> _{Ic}	1 ksi √in	1.10 MN/m ^{3/2}
Surface energy, <i>γ</i>	1 erg/cm ²	1 mJ/m ²
Temperature, <i>T</i>	1°F	0.556 K
Thermal conductivity, <i>λ</i>	1 cal/s cm °C	418.8 W/m °C
	1 Btu/h ft °F	1.731 W/m °C
Volume, <i>V</i>	1 Imperial gal	4.546 × 10 ^{−3} m ³
	1 US gal	3.785 × 10 ^{−3} m ³
Viscosity, <i>η</i>	1 P (poise)	0.1 N s/m ²
	1 lb ft s	0.1517 N s/m ²