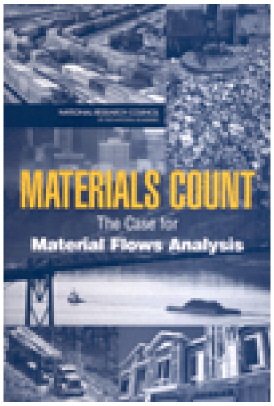


Materials Count: The Case For Material Flows Analysis

Committee on Material Flows Accounting of Natural Resources, Products, and Residuals, Committee on Earth Resources, National Research Council

ISBN: 0-309-51714-1, 144 pages, 6x9, (2004)

MATERIALS COUNT

The Case for
Material Flows Analysis

Committee on Material Flows Accounting of
Natural Resources, Products, and Residuals

Board on Earth Sciences and Resources

Committee on Earth Resources

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W., Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Department of Energy, Office of Energy Efficiency, Award No. DE-AM01-99PO80016 (Task Order No. DE-AT01-01EE41422); National Science Foundation, Award No. EAR-0122257; Environmental Protection Agency through National Science Foundation; U.S. Geological Survey Award No. 01-HQGR0068. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number 0-309-08944-1 (Book)
International Standard Book Number 0-309-51714-1 (PDF)

Library of Congress Catalog Card Number 2003114554

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, *http://www.nap.edu*

Cover: Design by Michael Dudzik. Photo courtesy of PhotoDisc, Inc. (upper left and right); Digital Stock Corp. (center and lower left); and Corbis Corp. (lower right).

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON MATERIAL FLOWS ACCOUNTING OF NATURAL RESOURCES, PRODUCTS, AND RESIDUALS

R. LARRY GRAYSON, *Chair*, University of Missouri-Rolla
DAVID T. ALLEN, University of Texas, Austin
BRADEN ALLENBY, AT&T Corporation, Bedminister, New Jersey
CORBY G. ANDERSON, Montana Tech, Butte
SCOTT R. BAKER, International Copper Association, New York, New York
DAVID BERRY, Department of Interior (*retired*), Annandale, Virginia
ROBERT COSTANZA, University of Vermont, Burlington
THOMAS E. GRAEDEL, Yale University, New Haven, Connecticut
JOYCE LEE, City of New York Office of Management and Budget, New York
WAYNE B. TRUSTY, ATHENA Sustainable Material Institute, Merrickville, Ontario, Canada
DIRK J.A. VAN ZYL, University of Nevada, Reno

Staff

TAMARA L. DICKINSON, Study Director
MONICA R. LIPSCOMB, Research Assistant (from February 2003)
EILEEN McTAGUE, Research Assistant (June 2002 to February 2003)
KAREN L. IMHOF, Senior Project Assistant

COMMITTEE ON EARTH RESOURCES

SUSAN M. LANDON, *Chair*, Thomasson Partner Associates, Denver, Colorado
JAMES C. COBB, University of Kentucky, Lexington
VICKI COWART, Consulting Geologist, Denver, Colorado
PATRICK CUMMINS, Western Governors' Association, Denver, Colorado
THOMAS V. FALKIE, Berwind Natural Resources Corporation, Philadelphia, Pennsylvania
MURRAY W. HITZMAN, Colorado School of Mines, Golden, Colorado
MICHAEL L. MENGE, U.S. Senate Committee for Energy and Natural Resources, (*retired*), Dover, Arkansas
JOHN N. MURPHY, University of Pittsburgh, Pennsylvania
DONALD L. PAUL, ChevronTexaco Corporation, San Ramon, California
MARK C. ROBERTS, Michigan Technological University, Houghton
JOAQUIN RUIZ, University of Arizona, Tucson
RUSSELL E. STANDS-OVER-BULL, Arrow Creek Resources, Inc., Pryor, Montana
R. BRUCE TIPPIN, North Carolina State University, Asheville
LAWRENCE P. WILDING, Texas A&M University, College Station
P. MICHAEL WRIGHT, Idaho National Engineering and Environmental Laboratory, Idaho Falls

Staff

TAMARA L. DICKINSON, Senior Program Officer
MONICA R. LIPSCOMB, Research Assistant
KAREN L. IMHOF, Senior Project Assistant

BOARD ON EARTH SCIENCES AND RESOURCES

GEORGE M. HORNBERGER, *Chair*, University of Virginia, Charlottesville
JILL BANFIELD, University of California, Berkeley
STEVEN R. BOHLEN, Joint Oceanographic Institutions, Washington, D.C.
VICKI COWART, Consulting Geologist, Denver, Colorado
DAVID L. DILCHER, University of Florida, Gainesville
ADAM M. DZIEWONSKI, Harvard University, Cambridge, Massachusetts
WILLIAM L. GRAF, University of South Carolina, Columbia
RHEA GRAHAM, New Mexico Interstate Stream Commission, Albuquerque
V. RAMA MURTHY, University of Minnesota, Minneapolis
DIANNE R. NIELSON, Utah Department of Environmental Quality, Salt Lake City
RAYMOND A. PRICE, Queen's University, Kingston, Ontario
MARK SCHAEFER, NatureServe, Arlington, Virginia
BILLIE L. TURNER II, Clark University, Worcester, Massachusetts
THOMAS J. WILBANKS, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Staff

ANTHONY R. DE SOUZA, Director
PAUL M. CUTLER, Senior Program Officer
TAMARA L. DICKINSON, Senior Program Officer
DAVID A. FEARY, Senior Program Officer
ANNE M. LINN, Senior Program Officer
RONALD F. ABLER, Senior Scholar
KRISTEN L. KRAPF, Program Officer
LISA M. VANDEMARK, Program Officer
YVONNE P. FORSBERGH, Research Assistant
MONICA R. LIPSCOMB, Research Assistant
VERNA J. BOWEN, Administrative Associate
JENNIFER T. ESTEP, Administrative Associate
RADHIKA S. CHARI, Senior Project Assistant
KAREN L. IMHOF, Senior Project Assistant
TERESIA K. WILMORE, Project Assistant
WINFIELD SWANSON, Editor

Acknowledgments

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making their published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Patrick Atkins, Alcoa Inc.
Robert U. Ayres, INSEAD, Center for the Management of Environmental and Social Responsibility
Robert W. Bartlett, University of Idaho, (*emeritus*)
Graham A. Davis, Colorado School of Mines
Robert A. Frosch, Harvard University
J. Brent Hiskey, University of Arizona
Richard T. Jaffre, Texas Industries, Inc.
Brad Mertz, Utah Valley State College
Mark Schaefer, NatureServe
Valerie Thomas, Princeton University

Although the individuals listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final report before its release. The review of this report was overseen by Gordon E. Forward, U.S. Business Council for Sustainable Development, Chairman Emeritus. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the NRC.

Preface

Other the past century, increasing consumption of materials and energy to meet growing industrial and population demands has strained both society and the ecosystem. For about a decade the world community has been working toward better tracking of material and energy flows through the economy and into the environment. Some nations have begun developing indicators of total material requirements, efficiency of materials use, and the impacts on the environment, while realizing that social and economic impacts must be assessed and integrated in making related public policy.

Formal economy-wide material flows accounts and analyses began in Austria in the 1990s and then in other European countries, and the efforts have been coalescing now into a framework with guidelines at the European Union level. Japan has been pursuing similar developments. Although not yet establishing formal material flows accounts, the United States has a long history of tracking mineral and energy flows through the U.S. Geological Survey, the Bureau of Mines, and the Energy Information Administration. The U.S. Environmental Protection Agency, the U.S. Geological Survey, the Department of Energy, and the National Science Foundation, in sponsoring this study, realized the need to examine the potential benefits of material flows accounting and analyses, directed toward making better public policy related to the interactions among industrial processes, the economy, and the environment.

This report examines the current state of material flows accounting, the uses and usefulness of the accounts and analyses, and related issues. Conclusions on these topics are given, along with recommendations aimed at implementing an effective material flows accounting system that could be used to enhance public policy making on the environment, materials, and energy. The report was prepared based on deliberations and discussions among members of the committee, who shared their expertise freely and dedicated themselves to many hours of report writing and revision as well as careful review of a number of report drafts. The committee was completely engaged during the study, and a pleasure to work with throughout.

The committee is grateful to a number of experts on material flows and industrial ecology at the U.S. Environmental Protection Agency, the U.S. Geological Survey, the Department of Energy, and the National Science Foundation, who participated in open information-gathering sessions. Gratitude is also expressed to many other professionals from industry, associations, nongovernmental organizations, and other state and federal agencies that participated in the process. For the study, we are indebted to Anthony de Souza, Director, Board on Earth Sciences and Resources, and the outstanding assistance of Tammy L. Dickinson, study director, who guided the committee through the entire process and kept us focused and organized. Finally, a great debt of gratitude is owed to the expert reviewers who helped us achieve a cogent and accurate report.

Larry Grayson, *Chair*

Contents

Executive Summary

Rising population and industrial growth are placing increasing strains on a variety of material and energy resources and the global environment. Understanding how to make the most economically and environmentally efficient use of materials will require an understanding of the flow of materials from the time a material is extracted, through processing, manufacturing, use, and its ultimate destination as a waste or reusable resource. It will also require knowledge of the environmental and societal impacts of the flows. These considerations are key to the overall application of sustainable development in practice.

Material flows data have informed national security, industrial, and public policy decision makers for decades. For national security purposes it is important to recognize that the United States currently imports more than half its use of dozens of commodities. Many of the materials are strategic for the economic growth and security of the nation, and in many cases, the primary sources of the materials are in regions of political instability. The most obvious example is the U.S. dependence on foreign oil.

The need to collect material flows information to support national security decisions may be self-evident, but other uses of material flows information are also important though perhaps less obvious. Analyses of material flows data have prevented technologies that would severely strain material availability (e.g., the contemplated switch from tin-lead solder to a formula using bismuth and indium) from moving forward. Analyses of material flows data have also led to surprising and counter-intuitive insights into environmental pollutants. For example, a material flows study identified dental facilities, not heavy industry, as the largest wastewater source of mercury releases into the New York Harbor. In addition to identifying potential environmental concerns, material flows information can also be used to develop strategies for preventing environmental releases. Material flows data, for example, revealed that the widespread use of pressure-treated lumber over the past 30 years has created large stocks of arsenic in building materials that are now nearing the end of their useful life. Material flows information can thus allow for the development of effective strategies for preventing the widespread release of arsenic into the environment.

These simple examples demonstrate that such data can inform a variety of decision makers, but to be most useful the material flows data should be systematically organized into accounts. Material flows accounts track the movement of matter into and out of a system of interest, using methodically organized accounts and denoting the total amounts that remain for a defined period to create a stock. When material flows are organized into accounts, they are in some senses similar to financial accounts, a routine part of the business of corporations, government, and organizations of all kinds. Financial accounts include such information as the balance between revenue and expenses, cash flow, reserves, and competitive financial position. National and international agreements define the terms used in financial reports, the procedures for reporting, provisions for auditing, and so forth. Decision makers rely on this information so heavily that our modern world is essentially unthinkable without it. As with financial accounts, material flows accounts include inputs, outputs, and accumulations in stocks and could, if implemented, become critical for planning and decision making.

Because of the potential of material flows accounting for public policy making, the National Research Council was commissioned by the Department of Energy, U.S. Environmental Protection Agency, National Science Foundation, and U.S. Geological Survey to establish a Committee on Material Flows Accounting of Natural Resources, Products, and Residuals to undertake a study to address material flows accounting issues. The committee was asked to do the following:

- Examine the usefulness of creating and maintaining material flows accounts for developing sound public policy on the environment, materials, and energy.
- Evaluate the technical basis for materials flows analysis.
- Assess the current state of material flows information, including what data are collected, where they reside, quality, scale, and completeness of the data; formats; accessibility; and the tools and methods available for analyzing the data.
- Describe how the public and private sectors are currently using

this information and how material flows accounts can be improved through partnerships or access to additional data.

- Determine who should have institutional responsibility for collecting, maintaining, and providing access to additional data for material flows accounts.

The committee did not undertake a cost-benefit analysis when considering the usefulness of creating and maintaining material flows accounts. However, the committee did look qualitatively at the cost impact of several implementation options and the recommendations in general.

USES AND USEFULNESS

In a material flows account, the entries refer to exchange of quantities of a specific material rather than to monetary exchanges. If multiple materials are involved, a separate account is established for each material. A manufacturer of power cables, for example, would have accounts for the copper that conducts electricity and for the polymer that encases the copper. A country would generate data, for example, for lead that is mined, processed, exported, discarded, and recycled. As with financial accounts, which are used to construct economic input-output tables and provide information on economic linkages throughout the economy, material flows accounts may be used to construct physical input-output tables that describe material linkages.

Material flows databases and analyses are already well established in a variety of U.S. government agencies. Material flows analyses at the processing plant, corporate, and national levels are also being done by private organizations. *The committee concludes that analyses using material flows data have already proven useful.* However, the data are not being used as effectively as they could be if there were a consistent framework and system to collect, analyze, and distribute the information routinely and to link data at various levels.

Material flows accounts are new enough that their potential value is not yet universally appreciated or even comprehensively demonstrated. Their utility has been amply demonstrated in a number of case studies, however. The committee notes that the existence of a formal economy-wide material flows accounting system and of a national physical input-output table would likely provide a range of benefits, including the following:

- Federal and state agencies would gain better information on the sources and uses of the mineral and renewable resources within their responsibilities.

- In the pursuit of continuous improvement of economic and environmental performances, corporations would have better information on current and potential supplies of the materials they use, on potential positive and negative environmental impacts of the materials, and on substitutes they could use to supplant undesirable materials in their systems and processes.
- Users of the material accounts would be able to track sources, flows, and dispositions of materials to determine more effective strategies for improving environmental and economic performances as well as efficiency of resource use.
- National security strategists would have better data on the sources of materials critical to the U.S. economy and to national security—from energy materials, to rare metals, to widely used material resources.

The committee concludes that the establishment of material flows accounts and their use in analyses will improve public policy making. Proper accounting requires the use of a standardized structure and specified principles. **Therefore, the committee recommends that a structured material flows accounting framework that can accept and integrate existing and future data be established.**

MATERIAL FLOWS INFORMATION IN THE UNITED STATES

Even though the United States has no organization or agency that is mandated to gather information and construct comprehensive material flows accounts, there are many sources of data on material flows. A number of federal agencies (U.S. Geological Survey, Environmental Protection Agency, Department of Energy, and Department of Agriculture) gather material flows data relevant to their organizational missions and responsibilities. Although the data are not coordinated or integrated for analysis or public policy-making purposes and are not adequate to construct material flows accounts, the data could be used to begin populating national material flows accounts. The committee recognizes that the present state of information at the federal level is useful to the agencies that collect it, but is inadequate to construct comprehensive material flows accounts.

The committee concludes that there are some good sources of data relevant to material flows, but the data are not yet adequate to populate formal material flows accounts. The committee further concludes that these inadequacies impede the development of sound public policy and business decisions. **The committee recommends that a national-level effort be initiated to identify and fill significant data gaps that presently impede the development of effective material flows accounts**. Integration and modest supplementation of existing data acquisition programs are thus extremely valuable.

RESEARCH CHALLENGES FOR MATERIAL FLOWS ACCOUNTING

The early development of material flows accounts will raise important issues concerning the scope of the accounts, the data in them, and the tools and analytical approaches to studying stocks and flows. Many areas of potential utility (that is, of the assessments that follow from studies based on information in accounts) also remain to be fully explored. These important issues include spatially discrete measurements (potentially important for considerations of materials reuse), dynamic assessments (flows over time), multilevel assessments (e.g., how state-level material flows accounts are related to national material flows accounts), and culturally related assessments (e.g., how changes in population diversity will be reflected in materials use).

Working together, government agencies, the industrial sector, researchers, and other users of the data will have to capture the issues that arise during the development and use of material flows accounts, which will require further research for solution or better understanding. Indeed, with financial accounting as a model, it appears virtually impossible to contemplate a material flows accounting program that does not include research activities. *The committee concludes that a comprehensive material flows accounting program requires a research component that explores tools and analytical approaches to studying stocks and flows that vary over space and time, that treat multiple organizational levels, and that explores the complexities and benefits of cycles linked by nature, by technology, or by a combination of the two.* **The committee recommends that relevant government agencies support research related to material flows accounting.**

IMPLEMENTATION STRATEGY

A successful implementation strategy for material flows accounting will be the key to its effective use in public policy making. An important element of the strategy would be the nature of the organization and its functionality. Clearly stating the mission and specifying the anticipated goals of the material flows accounting organization will be a necessary first step. An example, based in part on the European Union mission (Eurostat, 2001) statement follows:

> The mission of the Material Flows Accounting Office [organization] is to develop and maintain a common database system that will provide material flows information, which can be integrated into analyses of physical and economic systems, thereby permitting more robust public policy decision-making.

Although falling short of creating purposeful national material flows accounts, the United States possesses numerous databases, accounting based and statistical in nature, that could support the development of such accounts. Any movement toward the creation of material flows accounts requires that these data be available for incorporation. A successful implementation strategy for material flows accounting will be the key to its effective use in public policy making.

The committee concludes that the present level of data collection and analysis must be maintained as an essential foundation for initial development of structured material flows accounts. **The committee recommends that the present material flows data activities of the federal government, including those in the U.S. Geological Survey, U.S. Environmental Protection Agency, and Departments of Commerce and Agriculture, be maintained at least at their current levels of activity.** Budgetary support must be sufficient to allow the activities to continue at levels that will maintain the integrity of the present databases. Sufficient resources must be available to replace retiring personnel and to maintain the staffing levels. If a decision is made to establish a system of national material flows accounts, staffing levels in existing agencies would likely have to be enhanced to support the effort.

For the entire system of material flows accounts, analyses, and linkages to achieve success, it is important that a broad range of stakeholder experts be involved in the process to prioritize the incorporation of successive data. The material flows accounting effort must be supported by a core group of government representatives from agencies that assemble the primary and other data. Further, the material flows accounting process must be institutionalized through a core team comprised of interdisciplinary experts.

A well-conceived and well-executed material flows account should be multidimensional, requiring inputs from many sources, appropriate data management, and careful quality control of input data and analytical methods. Formal material flows accounting can be quite complicated, and an important aspect concerns the precision of the data and the accuracy of account results. Flawed or inadequate material flows accounts may lead to inappropriate decisions and actions. As such, it is crucial that material flows accounting activities be highly participatory and collaborative among parties with appropriate material flows accounting expertise, relevant process knowledge, and familiarity with the appropriate data sets.

Participants as partners in material flows accounting activities are important to the quality of accounting products. The quality is enhanced when partners are knowledgeable and actively engaged in the process and their legitimate concerns are appreciated and respected. *The committee concludes that partnerships are critical to developing and maintaining material flows accounts.* The most effective partnerships are those based on stable, trusting relationships established over time, where all gain from the compiled information, and that such partnerships are critical to the success of material flows accounting. **The committee recommends that any process for developing material flows accounts be based on a partnership approach.** Partnerships among all relevant stakeholder groups (e.g., government agencies, industry, and nongovernmental organizations) should be encouraged, with strong leadership, representation appropriate to the material flows accounts under consideration, active participation in the accounting activity, and regard for each participant's motivations and incentives for participating. **The committee recommends that the system be designed to allow for the inclusion of proprietary data, while protecting business confidentiality.** Data in the material flows accounts should be available to the greatest extent feasible, unless proprietary issues demand otherwise.

The committee notes that formidable work will be required in designing a robust system of material flows accounts. *Having examined several options, the committee concludes that an independent organization is the most likely option to ensure success of material flows accounting in the United States.* The committee believes that it will help the partnership process if the organization is separate from existing data providers. **Accordingly, the committee recommends that an independent organization, comprised of interdisciplinary experts, be created and funded through a formal process.** The organization may be formed through creation of a partnership-based consortium of industry, government, academia, and other committed stakeholders; a competitive solicitation; or some other process.

The establishment of material flows accounts and their use in material flows analyses will improve public policy making. Ultimately, the accounts and analyses using them can be coupled with economic, quality-of-life, and environmental information to give integrated-impact input on public policy. Much of the progress in this arena will stem from ongoing research, which will run concurrently with the development of material flows accounts.

The strategy for successful implementation of material flows accounts is important to ensure downstream successes in using them. By using a partnership approach, the accounts and their uses would be enhanced, and through this enhancement, linkages with other databases on the economy, the environment, and social and cultural information could lead to the type of holistic public policy making necessary for a progressively more complex society.

1

Introduction

Humans have processed and used materials since the dawn of civilization. For most of this time, small populations and low levels of technology meant that rates of materials extraction, use, and disposal were low. The situation changed significantly as the Industrial Revolution began. In the late nineteenth century and in the latter half of the twentieth century, the amount of material used in economic activity exploded (See Plate I).

Concerns over expanded rates of material use and the long-term availability of material resources were the basis for the report of the Paley Commission (President's Materials Policy Commission, 1952), which documented the importance of systematic tracking of material flows. Government agencies responded by (or had already been active in) monitoring the rates of use of minerals, forest products, and fuels. These activities continue and have been gradually expanded to include additional material flows, such as environmental emissions. These are all components of a comprehensive approach to sustainable development as discussed further in Chapter 3.

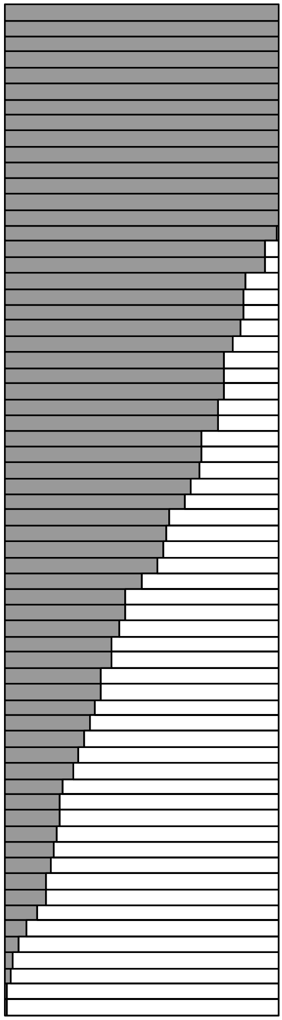
Efforts at tracking sources and flows of materials have allowed public and private sector decision makers to answer critical questions for decades. Where were the metals needed to supply the growth of American manufacturing? Where were the construction materials needed for the growth of American cities, housing, and highways? Where were the energy resources to keep transportation moving, keep the lights on and the machinery turning, and keep the heat on in the winter and the air conditioning in the summer? Where were the alternate sources of supply or substitutes for strategic materials necessary to support American industry and national security? What were the environmental consequences of the material and energy flows?

Answering these questions will continue to be important for national security, economic growth, and environmental decision making. For example, for national security purposes it is important to recognize that the United States currently imports more than half its use of dozens of commodities (USGS, 2002a) (Figure 1.1). Many of these materials are strategic for the economic health and security of the nation, and in many cases, the primary sources of the materials are in regions of political instability. The most obvious example of this material dependence is oil. In October 2002, 63 percent of the petroleum used in the United States (9.5 million barrels per day) was imported (EIA, 2002a). However, other important though less obvious examples abound. For example, fluorspar is the primary raw material for hydrofluoric acid, which is used directly or indirectly in the manufacture of aluminum, gasoline, insulating foams, refrigerants, steel, and uranium (USGS, 2003a). The United States imports all of its fluorspar, and some of the imports come from regions that have volatile trade relationships with the United States. Figure 1.1 shows that these situations are relatively common.

The need to collect material flows information to support national security decisions may be self-evident, but other uses of material flows information have been unexpected. One important function of material flows accounts is to help firms and the economy innovate efficiently. In particular, such data can guide the development of technologies that are possible at actual production levels. For example, in the early 1990s, the electronics industry was contemplating a switch from tin-lead solder, the universal standard, to solder compositions that avoided the use of lead, an environmental pollutant (Sidebar 1.1). In this case, analysis of materials flows prevented an inappropriate technology with high cost and a problematic future from moving forward. Improved alternatives using more common metals have now begun to appear in the electronics market.

Analyses of material flows data have also led to surprising insights into sources of environmental pollutants. When a team assembled by the New York Academy of Sciences used material flows data to identify the sources of mercury in New York Harbor, the data revealed that releases from dental facilities, not heavy industry, were the largest wastewater contributor (de Cerreno et al., 2002).

An assessment of material flows was a critical element of the cement industry's strategic vision, developed through the World Business Council for Sustainable Development (World Business Council for Sustainable Development, 2002). These flows included not just the raw materials of



Commodity	Percent	Major Import Sources (1997-2000)[1]
ARSENIC (trioxide)	100	China, Chile, Mexico
ASBESTOS	100	Canada
BAUXITE and ALUMINA	100	Australia, Guinea, Jamaica, Brazil
COLUMBIUM (NIOBIUM)	100	Brazil, Canada, Germany, Russia
FLUORSPAR	100	China, South Africa, Mexico
GRAPHITE (natural)	100	China, Mexico, Canada, Brazil
MANGANESE	100	South Africa, Gabon, Australia, Mexico
MICA, sheet (natural)	100	India, Belgium, Germany, China
QUARTZ CRYSTAL (industrial)	100	Brazil, Germany, Madagascar
STRONTIUM	100	Mexico, Germany
THALLIUM	100	Belgium, Canada, Germany, United Kingdom, France
THORIUM	100	France, Canada, Japan, Singapore
VANADIUM	100	Canada, South Africa, China, Austria
YTTRIUM	100	China, Japan, United Kingdom, Germany
GEMSTONES	99	Israel, India, Belgium
BISMUTH	95	Belgium, Mexico, United Kingdom, China
INDIUM	95	Canada, China, Russia, France
TIN	88	China, Peru, Indonesia, Brazil, Bolivia
BARITE	87	China, India, Canada, Mexico
PALLADIUM	87	Russia, South Africa, Belgium, United Kingdom
ANTIMONY	86	China, Mexico, South Africa, Belgium, Bolivia
DIAMOND (natural)	83	United Kingdom, Switzerland, Ireland, Belgium
POTASH	80	Canada, Russia, Belarus
STONE (dimension)	80	Italy, Brazil, Canada, India
TANTALUM	80	Australia, China, Thailand, Japan
CHROMIUM	78	South Africa, Kazakhstan, Russia, Turkey, Zimbabwe
COBALT	78	Finland, Norway, Canada, Russia
IODINE	72	Chile, Japan, Russia
TITANIUM MINERAL CONCENTRATES	72	South Africa, Australia, Canada, Ukraine
RHENIUM	71	Chile, Kazakhstan, Germany, Russia
RARE EARTHS	68	China, France, Japan, United Kingdom
PLATINUM	66	South Africa, United Kingdom, Germany, Russia
ZINC	60	Canada, Mexico, Peru
TUNGSTEN	59	China, Russia, Germany, Portugal
TITANIUM (sponge)	58	Russia, Japan, Kazakhstan
NICKEL	56	Canada, Norway, Russia, Australia
PEAT	50	Canada
MAGNESIUM METAL	44	Canada, China, Russia, Israel
SILVER	44	Mexico, Canada, Peru, United Kingdom
SILICON	42	Norway, South Africa, Russia, Canada
BERYLLIUM	39	Russia, Canada, Germany, Kazakhstan
MAGNESIUM COMPOUNDS	39	China, Canada, Australia, Austria
ALUMINUM	35	Canada, Russia, Venezuela, Mexico
PUMICE	35	Greece, Italy, Turkey
DIAMOND (dust, grit, and powder)	33	Ireland, China, Russia
COPPER	31	Canada, Chile, Peru, Mexico
NITROGEN (fixed), AMMONIA	29	Trinidad and Tobago, Canada, Mexico
VERMICULITE	27	South Africa, China
GYPSUM	25	Canada, Mexico, Spain
CEMENT	21	Canada, Thailand, China, Venezuela, Greece
GARNET (industrial)	20	Australia, India, China
LEAD	20	Canada, Mexico, Australia, Peru
MICA, scrap and flake (natural)	19	Canada, India, Finland, China
PERLITE	18	Greece
SALT	17	Canada, Chile, Mexico, The Bahamas
IRON and STEEL	15	European Union, Canada, Japan, Mexico
IRON ORE	15	Canada, Brazil, Venezuela, Australia
SULFUR	12	Canada, Mexico, Venezuela
IRON and STEEL SLAG	8	Canada, Italy, Brazil, France
BROMINE	5	Israel, United Kingdom, Belgium, Netherlands
CADMIUM	3	Canada, Australia, Belgium, Germany
PHOSPHATE ROCK	2	Morocco
STONE (crushed)	1	Canada, Mexico, The Bahamas
TALC	1	China, Canada, France, Japan

[1]In descending order of import share

FIGURE 1.1 2001 U.S. net import reliance for selected nonfuel mineral materials. SOURCE: USGS, 2002a.

SIDEBAR 1.1
Lead Solder

In the early 1990s, the United States was considering restrictions on the use of lead solder in electronic fabrication, driven primarily by concerns about the toxicity of lead. The electronics industry began moving toward a number of options, including bismuth- and indium-based alloy alternatives, and conductive epoxies containing metals such as silver. Material flows data, incorporated into the analysis of lead alternatives, illustrated several important points (Graedel and Allenby, 1995). First, the amount of lead used in electronic solder was very small (about 0.7 percent of U.S. domestic consumption). Second, production data on indium and bismuth indicated that both mining and processing capabilities, and reserves, were inadequate to support the scale of demand that widespread substitution of bismuth, indium, or silver alloys would imply. Concentrations of bismuth, silver, and indium in ores were much lower than concentrations of lead, meaning that more mining activity and generation of overburden, as well as more processing, with their attendant environmental and economic costs, would be required to produce equivalent amounts of metal. Moreover, most bismuth was being produced as a by-product of lead mining, so substantially increasing the demand for bismuth would encourage lead mining and production. This simple material flows analysis helped prevent what might have been a costly and serious misdirection of technological evolution in the electronics industry (Allenby et al., 1992). As a result of this experience, not only was industry research and development targeted to more potentially beneficial alternatives, but those alternatives were investigated more systemically. In short, the lead solder experience taught the electronics industry to use material flows data as a routine part of making its operations and research more efficient and productive.

cement, but also the myriad of materials that are used as supplementary fuels and feed supplements such as tires, waste plastics, electric arc furnace dust, and liquid hydrocarbon wastes. The locations and availabilities of these materials will drive future economics in the cement industry as much as the location and availability of limestone, clay, and sand.

As illustrated by the previous examples, material flows information can be significant in identifying potential environmental concerns, allowing preventive action. For example, material flows data reveal that over the past 30 years, the widespread use of pressure-treated lumber has created large stocks of arsenic in building materials that are now nearing the end of their useful life (Sidebar 1.2). Knowledge of the use patterns and spatial distribution of this stock of arsenic, through material flows data,

SIDEBAR 1.2
Arsenic in Wood

For the past 30 years, arsenic has been used in the United States at a relatively constant rate of 20,000 tons per year. The arsenic has been imported and its primary use has been in pressure-treated wood, which contains chromated copper arsenate. Treated lumber replaced other wood preservation processes, such as treatment with creosote, and this lumber has become ubiquitous in home construction and other applications. Hundreds of thousands of tons of arsenic have now accumulated in homes and other built systems.

Concerns about the potential for this arsenic to leach into the environment (Lebow, 1993; Stilwell and Gorny, 1997) have led to the development and use of alternative wood treatments. Over the next several years, arsenic will be phased out as a wood preservative. Yet, hundreds of thousands of tons of arsenic will remain in built systems and ultimately this wood will rot, be landfilled, or be incinerated. Developing effective strategies for preventing this arsenic from being released to the environment will depend on knowledge of the quantities and spatial distribution of chromated copper arsenate lumber in housing and other stocks and estimates of the rate at which the materials will enter waste streams. This information can be assembled from material flows and census information.

SOURCE: Rejeski, 1998.

could allow for the development of effective strategies for preventing the widespread release of arsenic into the environment.

These limited examples, which are expanded on in Chapter 4, show that material flows data inform national security, industrial, and public policy decisions. Yet decision makers now face a new generation of questions that require integration of economic, environmental, material flows, and energy flows information. On what fuel infrastructure should a next-generation transportation system rely? What are the economic, material flows, energy flows, and environmental implications of nanotechnologies and biotechnologies? What should be the disposition of electronic products at the end of their useful life? How can global environmental loads of mercury and nutrients be most cost-effectively reduced? Answering these questions will require material and energy flows data and economic information that are much more complete and integrated than current data. As examples in this chapter have illustrated, decision makers without access to more systematically integrated material flows information could have a greater potential for making costly, ineffective decisions.

The flows of mercury provide a rich example of the need for more integrated material flows information. A variety of regulatory strategies are being developed for reducing mercury releases into the environment, including reducing the use of mercury in products such as electrical switches and requiring the removal of mercury from the stack gases of coal-burning power plants. The effectiveness of these strategies in reducing the accumulation of mercury in the food chain will depend on the interaction between the environmental releases and the global environmental processing of mercury that allows it to bioaccumulate. The eventual effectiveness of the policies will depend on whether current analyses of mercury stocks and flows, which have significant uncertainty, are accurate.

STUDY AND REPORT

Understanding how to make the most economically and environmentally efficient use of materials will require an understanding of the flow of materials from the time a material is extracted, though processing, manufacturing, use, and its ultimate destination as a waste or reusable resource. It will also require knowledge of the environmental and societal impacts of the flow.

The National Research Council was commissioned by the Department of Energy, U.S. Environmental Protection Agency, National Science Foundation, and U.S. Geological Survey to establish a Committee on Material Flows Accounting of Natural Resources, Products, and Residuals to undertake a study to address material flows accounting issues. The committee consisted of 11 experts from academia, industry, and government with expertise in industrial ecology, mining and chemical engineering, sustainable design and construction, ecological economics, and toxicology. Biographical sketches of the committee members are provided in Appendix A.

The statement of task asked the committee to examine material flows accounting. Specifically, the committee

- examined the usefulness of creating and maintaining material flows accounts for developing sound public policy on the environment, materials, and energy;
- evaluated the technical basis for material flows analysis;
- assessed the current state of material flows information, including what data are collected, where they reside; quality, scale, and completeness of the data; formats; accessibility; and the tools and methods available for analyzing the data;
- described how public and private sectors are currently using this

information and how materials flow accounts can be improved through partnerships or access to additional data; and

- determined who should have institutional responsibility for collecting, maintaining, and providing access to additional data for material flows accounts.

The committee did not undertake a cost-benefit analysis when considering the usefulness of creating and maintaining material flows accounts. However, the committee did look qualitatively at the cost impact of several implementation options and the recommendations in general.

To address its charge, the committee gathered, synthesized, and analyzed information by holding three information-gathering meetings between July 2002 and September 2002. The meetings included presentations by and discussions with the sponsors; personnel from government programs; and representatives of industry, academia, and environmental organizations from both the United States and abroad (Appendix B). The full committee also met twice in closed session for discussion and writing. As background material, the committee reviewed several documents and materials including pertinent National Research Council reports, technical reports, and literature published through December 2002.

This report is intended for multiple audiences. It contains advice and information for the sponsors as well as for other federal agencies, policy makers, consultants, scientists, and engineers. Chapter 2 defines materials and material flows accounting for the purposes of this report and provides some historical context. Chapter 3 places material flows accounting, analysis, and issues in a broader societal context. Chapter 4 provides an overview of the uses and usefulness of the applications of material flows accounting. Chapter 5 recounts current sources of material flows information in the United States and gaps in data, and examines the challenges of integrating the numerous components involved in material flows analysis. Chapter 6 describes how material flows accounting could benefit from effective partnerships and outlines key issues to forming partnerships. Chapter 7 discusses research issues related to material flows accounting, including its linkage with the grand cycles of nature and how it may be more useful. Chapter 8 describes an implementation scheme for the successful development and use of material flows accounts.

2

Material Flows Accounting Definitions and System Structures

In its simplest sense, material flows accounting is a method for tracking the movement of matter into and out of a system of interest from and to the environment, using methodically organized accounts, and denoting the total amounts that remain in the system to create a stock. For clarity (adopted from Eurostat, 2001), material inputs to a system generally include all solid, liquid, and gaseous materials that enter the economy for further use in production or consumption processes. The materials may or may not be toxic or hazardous in nature, or potentially so, and the flows may range from very large to trace levels. Outputs to the environment generally include all materials that flow into the environment from the system either during or after production or consumption processes. One of the purposes of establishing a material flows accounting system is for examining flows to achieve a mass balance for one, some, or all materials of interest, which requires memorandum items for balancing. Memorandum items are generally associated with an accounting system and would include, for example, the input of oxygen for combustion and biometabolism, the input of water for evaporation by animal and human metabolism, the output of water vapor from combustion, and the output of water evaporation from animal and human metabolism.

The system may be defined at various levels. For example, there can be national accounts for tracking flows at the level of a national economic system, comparable regional or state accounts, and corporate or even facility-level accounts defined in terms of the corporate or facility boundaries instead of geopolitical boundaries. However, there are different definitions and interpretations of material flows accounting, and it is important that appropriate terms be defined and used.

Confusion about terms will too easily translate into confusion about the nature of data collection and general program development that is being recommended by the committee. Clear definitions are also important to distinguish the accounting function from the use of data in material flows analysis—the subject that tends to dominate the literature. Without clear definitions of the various levels of material flows accounting, it would be difficult to properly structure a detailed discussion of benefits, reach conclusions, and make recommendations. This chapter therefore begins with an examination of existing definitions, before focusing on proposed definitions and a conceptual framework for use in the United States.

ACCOUNTING VERSUS ANALYSIS

Material flows data are often organized into accounts (e.g., flows of individual materials, flows in an industrial sector) that serve as the structured, formal repository of targeted data, making them accessible and useful while preserving this integrity through agreed accounting principles and practices. Whether considering national, regional, company, or facility-level accounts, material flows accounts provide the basis for tracking, comparing, and managing operational and environmental performances.

On a theoretical basis when material flows are organized into accounts, they are in some senses similar to financial accounts, a routine part of the business of corporations, governments, and organizations of all kinds. Financial accounts include information such as the balance between revenue and expenses, cash flow, reserves, and competitive financial position, and generally accepted accounting practices and definitions govern them. Decision makers rely on this information so heavily that our modern world is essentially unthinkable without it. Important trends in the economic or financial status of individuals, businesses, regions, states, countries, and coalitions (e.g., European Union) can be tracked accurately. As with financial accounts, material flows accounts include inputs, outputs, and accumulations in stocks and could, if implemented through well-defined procedures, become critical for calculating mass balances for targeted systems, creating trends in various derived indicators, planning public policy initiatives, and making decisions on key public policy issues. As with financial accounts, national and international agreements could be developed for populating, reporting, and auditing material flows accounts.

Material flows analysis, in contrast, most often deals with specific problems, regions, or materials, which means a much more focused approach. The work of the U.S. Geological Survey provides many examples of regional studies, including material flows research programs on abandoned mine lands, wetlands loss studies in the oil fields of south Louisiana, and natural resources damage assessment studies in Texas (Brown et al., 2000). Other excellent examples of substance-specific analyses are those dealing with arsenic, lead, and mercury, referenced elsewhere in this report.

"Inherent in materials flows analyses is the need for reliable, consistent data" (Wagner, 2002). The presumption is that good material flows analyses are dependent on good data being captured and maintained in material flows accounts. Ultimately the usefulness of material flows analyses depends directly on the quality of material flows accounts.

EXISTING DEFINITIONS

Three useful sources of definitional information are the New Jersey INFORM report, *Tracking Toxic Chemicals: The Value of Materials Accounting Data* (Dorfman and Wise, 1997); the international collaborative study on resource flows, *Resource Flows: The Material Basis of Industrial Economies* (Adriaanse et al., 1997); and the European Union methodological guide for economy-wide material flows accounts, *Economy-wide Material Flow Accounts and Derived Indicators: A Methodological Guide* (Eurostat, 2001). In this section, these sources are used to highlight definitional distinctions and related issues relevant to this study.

INFORM Report

New Jersey established a material tracking database, rather than a material flows accounting system, for toxic chemicals as a result of the 1984 Worker and Community Right to Know Act (P.L. 1984, c. 315, N.J.S.A. 34:5A-1.1 et seq.). This law required facilities to report quantities of chemicals transported into or out of a manufacturing facility, chemically converted in the production process, stored on-site, or generated as waste either to be released to the environment or transported off-site for recycling, treatment, or disposal. New Jersey's law requires reporting of the same substances as the U.S. Environmental Protection Agency's Toxics Release Inventory, but with considerably more detail regarding the flow characteristics (Sidebar 2.1). Materials tracking under this requirement can be described as a systematic tracking of raw materials and products as they move sequentially from one end of a facility to the other (Dorfman and Wise, 1997).

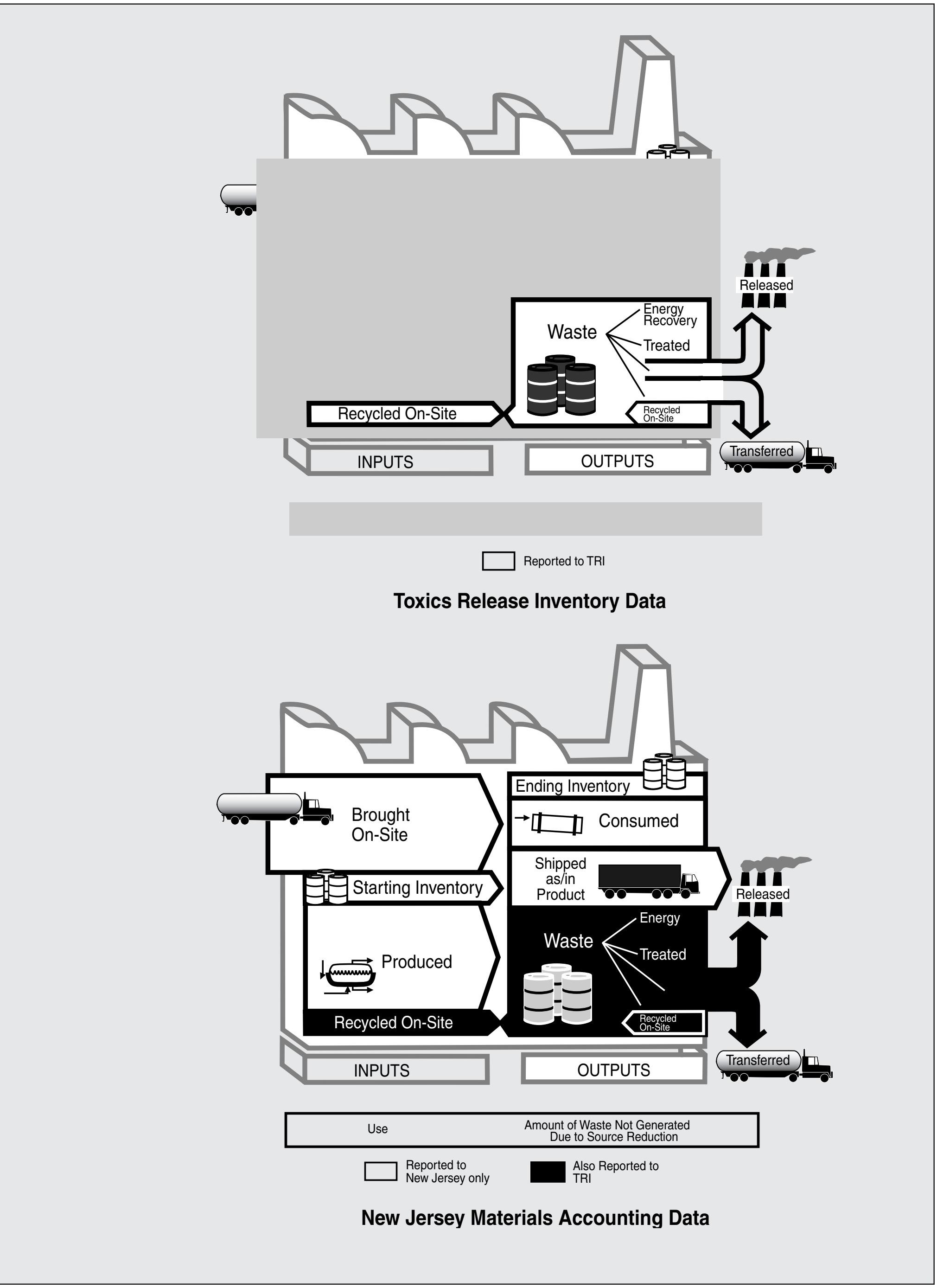
SIDEBAR 2.1
The New Jersey Material Tracking System

New Jersey state law requires that all "employers" (as defined in the Worker and Community Right to Know Act) submit at least one toxic chemical release inventory reporting form annually. This report, known as the New Jersey Release and Prevention Report, is used by the N.J. Department of Environmental Protection "to collect information on chemical throughput, environmental release, off-site transfer of chemicals, and pollution prevention information" (Dorfman and Wise, 1997).

Under the federal system, facilities with 10 or more employees that process more than 25,000 pounds, or use more than 10,000 pounds, of about 650 reportable chemicals annually are required to report their releases of these chemicals into the air, water, and land, as well as their transfers for treatment, disposal, or recycling including on-site recycling. The New Jersey system calls for reporting of the same 650 chemicals manufactured, processed, or utilized at a facility, with the threshold set at 10,000 pounds.

The New Jersey material tracking system provides a more complete picture of chemicals flowing through a facility than the Toxics Release Inventory. The New Jersey system requires industry to account for all of the inputs and outputs of each toxic species. The schematic diagrams illustrate the difference between the two systems. The diagram on the left depicts the tracked flows in the Toxics Release Inventory, and the diagram on the right shows the more comprehensive flow tracking under the New Jersey system.

SOURCE: INFORM, Inc., Tracking Toxic Chemicals: The Value of Materials Accounting Data, Dorfman and Wise, 1997. Used with permission.



Released
Waste
Energy Recovery
Treated
Recycled On-Site
Recycled On-Site
Transferred
INPUTS
OUTPUTS
Reported to TRI
Toxics Release Inventory Data
Ending Inventory
Brought On-Site
Consumed
Shipped as/in Product
Starting Inventory
Released
Waste
Energy
Treated
Produced
Recycled On-Site
Recycled On-Site
Transferred
INPUTS
OUTPUTS
Use
Amount of Waste Not Generated Due to Source Reduction
Reported to New Jersey only
Also Reported to TRI
New Jersey Materials Accounting Data

International Collaborative Study on Resource Flows

Responsive to the pressures of population growth and related economic, social, and environmental issues, an international collaboration evolved among Dutch, German, Japanese, and U.S. research institutes (Netherlands Ministry of Housing, Spatial Planning, and the Environment; Wuppertal Institute; National Institute for Environmental Studies; and World Resources Institute, respectively). The report *Resource Flows: The Material Basis of Industrial Economies* (Adriaanse et al., 1997) was written in an attempt to find "broadly acceptable new approaches and powerful new insights that can stimulate the global transformation" of societies.

In their joint work, the collaborators defined terms relating to material requirements in national economies, suggesting a set of physical accounts paralleling conventional national economic accounts. These terms include hidden flows, direct material input, and total material requirement. Hidden, often called indirect, flows are comprised of excavated and/or disturbed material flows and ancillary material flows, both of which are also defined. The group did not explicitly define a material flows account, or accounting, but the definitions provided set the stage for those subsequently developed as part of a European Union material flows accounting program.

European Union Guidelines

The European Union (EU) participates in a number of EU-wide and international environmental accounting activities. As a response to the policy demand for resource use indicators, Eurostat has developed a framework and guidance for establishing material flows accounts and material balances for the economy (Eurostat, 2001) (Sidebar 2.2). Representing a synthesis of already implemented material flows accounting systems among European Union member states, the guide is the first step toward uniform terminology, concepts, and a set of accounts and tables.

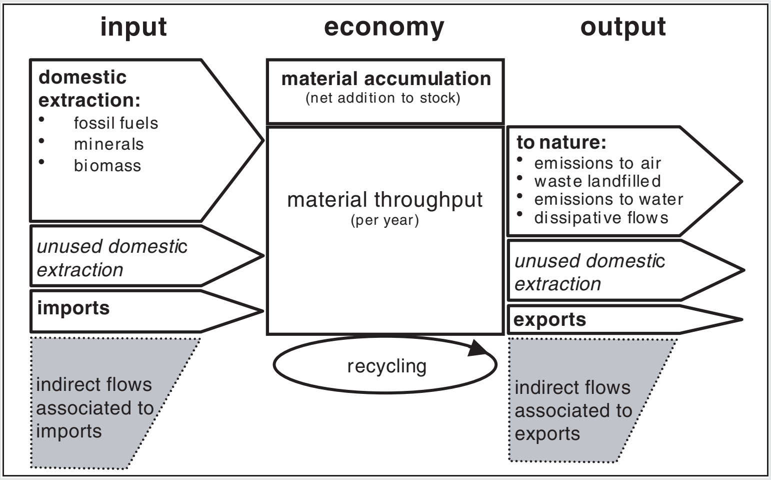
The European Union guidelines describe the key terms as follows:

- Economy-wide material flows accounts and economy-wide material balances ". . . show the amounts of physical inputs into an economy, material accumulation in the economy and outputs to other economies or back to nature. . ." (Eurostat, 2001).
- Physical input-output tables are ". . . the most comprehensive description of material flows between environment and economy as well as within the economy, distinguishing not only categories of materials but also branches of production" (Eurostat, 2001).

SIDEBAR 2.2
Material Flows Accounting in Europe

Most statistical institutes in Europe have the experience and data needed to compile economy-wide material flows accounts (Eurostat, 2001). The first economy-wide material flows accounts were compiled in Austria (Steurer, 1992). Today economy-wide material flows accounts exist in Austria, Denmark, Finland, Germany, Italy, the Netherlands, Sweden, and the United Kingdom within the European Union.

Research on material flows accounting continues to advance, and standard concepts and formats have been evolving. The European Commission, therefore, supported international research (Adriaanse et al., 1997; Matthews et al., 2000) as an important step toward developing internationally comparable data based on harmonized methods. The figure below shows the framework by which economy-wide material balances are accomplished, and it forms the basis for definitions of terms, which are discussed in this chapter.



Economy-wide material balance scheme (excluding air and water).

SOURCE: Eurostat, 2001. Copyright permission granted by the European Communities.

The following is especially critical to the committee's understanding of the European approach to material flows accounting and to the definitions proposed for use in the United States (Eurostat, 2001):

> Only flows are counted that cross the system boundary at the input side or at the output side. Material flows *within* the economy are not presented in economy-wide MFA [material flows accounts] and balances. Therefore, inter-industry deliveries of products, for example, are not described. However, they are described in Physical Input-Output Tables.

A later section contains the more explicit statement that "in economy-wide MFA the whole economy including production and consumption activities is a single black box. Only flows that cross the system boundary of the economy are recorded" (Eurostat, 2001).

In summary, the European Union makes a distinction between material flows accounts and physical input output tables:

- Material flows accounts cover flows into and out of the economy as a whole as well as accumulations.
- Physical input-output tables cover all of the flows internal to the economy as well as flows between the environment and the economy.

PROPOSED DEFINITIONS

The New Jersey, European Union, and other materials examined by the committee use the term *material flows accounting* to refer to methods for tracking the movement of materials from and to the environment, into and out of systems at various levels, from the nation to the facility. Care should be taken not to infer more than is meant by the term. There is no universally understood, more specific meaning for the term. To be more specific, a modifier, such as economy wide should be used, thereby making clear the boundaries and probable content of a given material flows account.

The committee agrees on the following definitions and general terminology:

1. Use terms such as "material flows accounting" and "material flows data," when writing generally about tracking material flows in physical terms.
2. Attach specific modifiers, such as "economy-wide," "national,", or "regional," to clearly define the boundaries for a specific set of material flows accounts.
3. Adopt the "black box" approach to material flows accounts for a

specified system (i.e., national, regional, or other specific system for which accounts are developed).

4. Use the physical input-output table terminology for material flows accounting within a system. This matches the economic input-output table terminology already in widespread use, making it easier to discuss the relationships between these two approaches to the same subset of flows. It also avoids confusion about the level of accounting data to which a given passage is referring.

CONCEPTUAL FRAMEWORK

Consistent with the Eurostat conceptualization of material flows accounts on an economy-wide basis (Eurostat, 2001, Figure 1, p. 9), the basic material flows concept is illustrated in Figure 2.1 for a generalized system. The figure shows the extraction of materials from the environment that flow directly into the economy or system of interest; material flows across the boundary of the system in the form of imports and exports; flows back to the environment in the form of emissions to air, water, and land; and the accumulation of material stocks. Stock accumulation can take any of a large variety of forms, from buildings to cameras, with materials routinely flowing into and out of the stock. Recycling and reuse represent a specific subset of material flows that contribute to maintenance of the stock of a material, without requiring additonal extractions or inflows of that material.

The figure also shows indirect, or hidden, flows associated with extraction, imports, and exports. As noted previously, hidden flows are comprised of excavated and/or disturbed materials and ancillary material flows that are ignored in economic flows accounts because they do not have economic value. An example of a hidden flow is the relocation of soil and rock strata that overlay a mineral deposit. The material must be removed before the ore can be extracted and used. The inclusion of such indirect flows is an important aspect of material flows accounting—the focus is on all material flows, not just those with economic value. This is the case even for imports, where the indirect flows are incurred outside the system.

The task of material flows accounting is to track all of these flows at a reasonable or practical level of detail for the system of interest. The feasibility of details may be related to the cost-benefit analysis of undertaking the effort, the adverse or beneficial impact on public health or the environment, or another rational evaluation. National accounts tracking these flows can be linked to form global accounts, just as regional accounts can be linked to trace flows through the national system more precisely.

As noted earlier, material flows accounts are distinguishable from

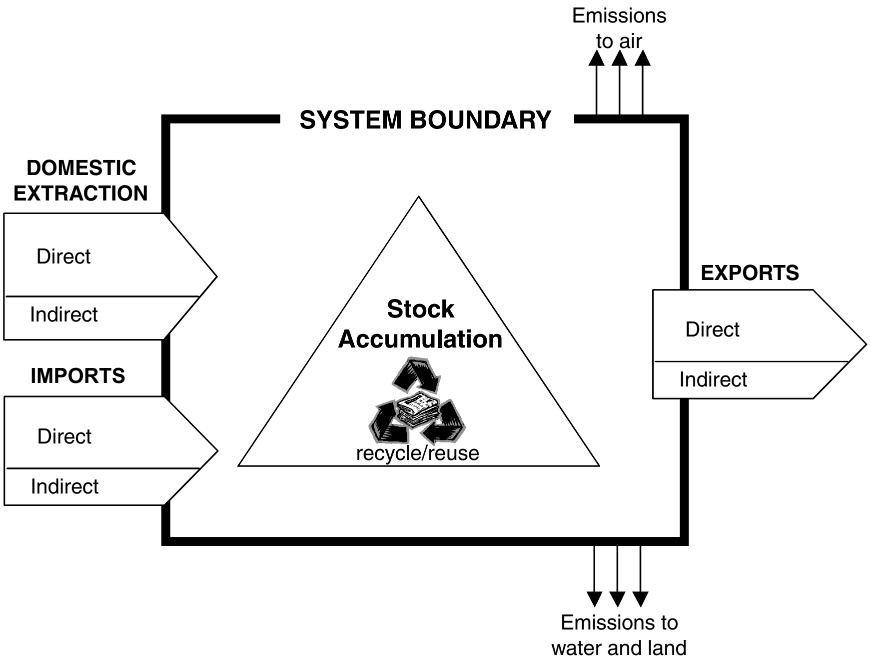


FIGURE 2.1 The basic concept of material flows as related to adopted definitions.

physical input-output tables, which give details on physical flows among and within sectors in a system of interest. Physical input-output tables, in turn, can be linked with economic input-output tables, which track only the economic flows or exchanges within the system in monetary terms (see Chapter 3). For example, an economy-wide material flows account for copper might trace the following:

- the flow of copper into the national economy as domestic input (e.g., from an Arizona copper mine) or through imports (e.g., from Chile);
- related hidden or indirect flows (e.g., overburden removed during mining and the waste portion of copper ore) and emissions (e.g., to air, from mine roadways, mill operations, refining);
- the totals that remain in the stock of products (e.g., autos), without distinguishing the products; and
- flows out of the economy as exports (e.g., in the form of finished products containing copper).

In contrast, a physical input-output table for copper would trace the following:

- flows of copper into and within the national economy from foreign or domestic sources, including hidden or indirect flows;
- the use of copper on a sector-by-sector basis (e.g., by the automotive industry, by the producers of wiring);
- flows from one sector to another through economic transfers (e.g., sale of wiring to the automotive industry), recycling, or reuse; and
- flows out of the economy, including hidden or indirect flows.

The corresponding economic input-output table could trace the following more restricted set of transfers:

- transactions covering the sale of copper among extractors, refiners, and basic processing or fabricating operations;
- sales of semi or fully manufactured copper products to final product manufacturers (e.g., sales of copper wire to the automotive industry, at which point copper is likely to be only one component);
- sales of final products (e.g., autos to consumers, at which point copper is likely to be a minor component); and
- possibly the sale of salvaged copper to refiners or other users.

The general relationship between material flows accounts and physical input-output tables is illustrated in Figure 2.2 by superimposing a grid

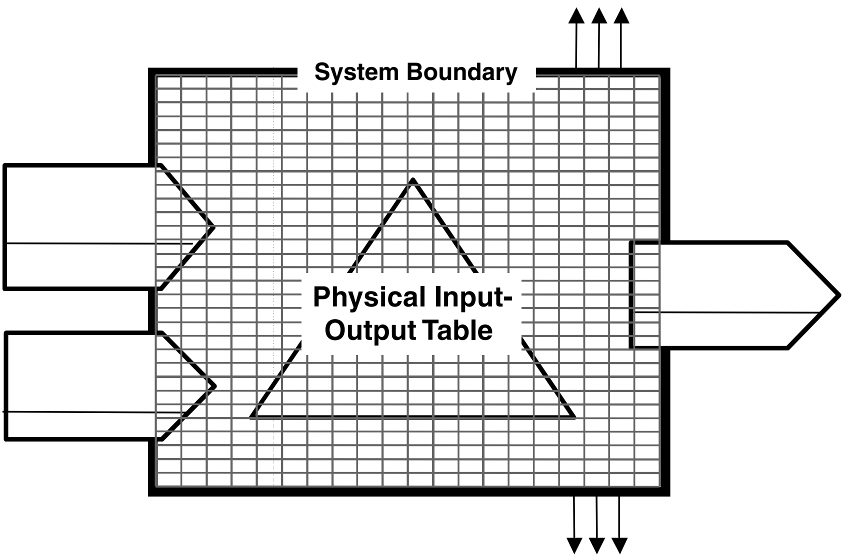


FIGURE 2.2 Relationship of physical input-output tables to material flows accounts. The major arrow and triangle figures represent the same entities as shown in Figure 2.1.

pattern representing the physical input-output table within the boundaries of the system of interest. The major arrow and triangle figures represent the same entities as shown in Figure 2.1.

The input-output tables would in reality be made up of many matrices, with rows and columns capturing the flows within and across sectors. For example, one subtable of a full physical input-output table could show the flows of individual nonferrous metals to various sectors and to branches within a sector; the flows of products containing the metals between sectors and as final products for consumption; and the flows of residuals to air, land, and water. Other subtables would cover flows of biomass, construction materials, fossil fuels, and ferrous metals. In short, physical input-output tables could show either the relationships across sectors and/or branches of the economy or among material groupings (i.e., materials used to produce other materials).

Like a material flows account, a physical input-output table covers hidden or indirect flows as well as flows that have monetary value. In contrast, an economic input-output table covers only those flows that reflect measurable economic transfers and would therefore correspond or map to only the portion of the physical input-output table that represents economic flows (Figure 2.3). Other parts of the physical input-output table

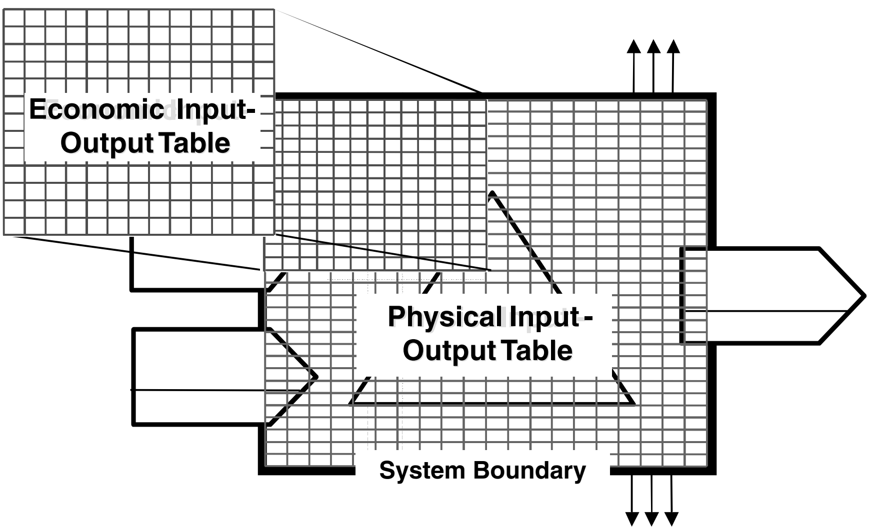


FIGURE 2.3 The relationship among economic input-output tables, physical input-output tables, and material flows accounts. The major arrow and triangle figures represent the same entities as shown in Figure 2.1.

represent the hidden flows and the outputs of residuals and pollutants from the economy to the environment. In addition, a physical input-output table can capture flows of natural materials through natural processes, including the "grand cycles" of water, nitrogen, phosphorus, and other materials through the natural Earth system.

The linkages between the economic and physical input-output tables represent both an important way of describing the implications of material flows for economic systems and an important research agenda. The research agenda is especially critical because conventional economic measurement and tracking account for a relatively small proportion of total flows, whereas it is the total flows that go to the heart of economic, environmental, and social sustainability. Research issues are presented comprehensively in Chapter 7.

DETAILS OF ACCOUNTING SYSTEM STRUCTURE

Beginning with Austria, the structure of economy-wide material flows accounts has been explored in Europe since the early 1990s (Steurer, 1992). A parallel effort was pursued in Japan during the same period (Japanese Environmental Agency, 1992). In ensuing years, similar developments occurred in seven other European Union countries, and the efforts have culminated in the drafting of a European Union guidelines document (Eurostat, 2001), which synthesizes among member states a formal structure for system accounts and procedures for using them.

In the United States, New Jersey implemented a materials tracking system focused on toxic materials, expanded beyond Environmental Protection Agency's Toxics Release Inventory, and Massachusetts implemented a system that collects data that give "the most complete picture of the conditions of use of a chemical at a facility, obtaining a description of each process (production unit), the range of amount of chemical use, and the percent change in waste by process, instead of facility-wide reporting as in New Jersey" (Dorfman and Wise, 1997). From these global efforts, significant insight into the structure of material flows accounts for effective use can be gleaned, and the details of two structures developed thus far are presented next.

European Union System Structure

The detailed structure of proposed material flows accounts, a synthesis of approaches by member states of the European Union for eventual standardization, is presented in Chapter 3 of *Economy-wide Material Flow Accounts and Derived Indicators: A Methodological Guide* (Eurostat, 2001). In preparing to develop material flows accounts, the structure is defined by a detailed classification of material inputs (Appendix C), of material outputs (Appendix D), and material stock changes (Appendix E).

Inputs to the economy-wide system include domestic extraction from the environment of fossil fuels, minerals, and biomass (used and unused [i.e., hidden flows]); imports of raw materials, semi-manufactured products, finished products, other products, packaging material, and waste imported for final treatment and disposal; and indirect flows associated with imports (raw material equivalent of imported products and unused extraction of imported products. Memorandum items for balancing inputs are included. Each of the aforementioned categories is broken down into greater detail, as shown in Appendix C.

A similar breakdown applies to material outputs (shown in Appendix D). Included are emissions and wastes to air, land, and water; dissipative uses of products and other dissipative losses; exports (same as for imports); disposal of unused domestic extraction; and indirect flows associated with exports. Memorandum items for balancing are also included.

Changes to stock are similarly defined, with details shown in Appendix E. Total additions embrace infrastructure and buildings, machinery, durable goods, and so forth. Removals similarly embrace infrastructure and buildings, machinery, durable goods, et cetera, but include dissipative losses. Net additions to material stock are total additions less removals.

Because of the enormity of water flows, Eurostat recommended that accounts for water flows be done separately, except for water contained in materials to attain balanced flows. Air was treated similarly, using it to complete material balances under combustion or oxidation situations. Since recycling data are sparse at present in the European Union, Eurostat recommended establishment of subaccounts, which may be implemented in material balance calculations when the accounts are sufficiently developed.

New Jersey System Structure

New Jersey's law, mentioned earlier, requires reporting of facilities for chemicals at threshold levels similar to reporting requirements under the Toxics Release Inventory. New Jersey facilities have expanded annual reporting, forming a material tracking database, that encompass the following data elements for chemicals that must be reported under the Toxics Release Inventory:

Inputs	Outputs
Starting inventory	Consumed
Brought on-site	Non-product output
Produced on-site	Shipped as (or in) product
Recycled on-site	Ending inventory

Details on data collection can be found in Appendix H of *Tracking Toxic Chemicals: The Value of Materials Accounting Data* (Dorfman and Wise, 1997), which gives New Jersey Department of Environmental Protection form DEQ-114. The figure given in Sidebar 2.1 above highlights the difference between the Toxics Release Inventory data and the New Jersey materials accounting data. Facilities covered under the Toxics Release Inventory report data on chemicals (in pounds) only for on- and off-site waste management (recycled, used for energy recovery, treated, and discharged to publicly owned treatment works) and direct releases to the environment (fugitive air emissions, point source air emissions, surface water discharges, injections underground in deep wells, and discharges to land). Toxics Release Inventory reporting does not give a comprehensive picture of toxic substances coming into a plant, being used or consumed at the plant, being stored at the plant, or leaving the plant as (or in) a product.

SUMMARY

Each of the accounting systems described in this section has a specific scope and related limitations. Economic input-output tables focus on the workings of the economy and track flows that represent only a subset of the total flows of concern from a sustainability perspective. Physical input-output tables go beyond the purely economic to capture the full range of flows within a system of interest, but are contained within that system. Material flows accounts operate at a different level of aggregation and offer the opportunity to reach beyond a system of interest, whether from the region to the nation or from nations to a global framework. They provide the basis for linking and integrating the full range of natural and social sciences research and data, and for describing and better understanding the intricately interconnected network of the global economy and environment as well as their impacts on people. Ultimately the key to forming and using material flows accounts successfully is to collect detailed data according to a defined structure on the quantities of targeted materials, their composition, their origin and destination, and other associated, salient characteristics such as toxicity. The next chapter examines the broader context for material and energy flows information.

3

Broad Context for Material and Energy Flows Information

The benefits of material flows accounting are more understandable if the historical and current context is clear. At the end of the nineteenth century, the United States economy was based primarily on agriculture, extractive industries, and manufacturing (Figure 1.1). Since then, developed economies have evolved to become primarily service economies. Although the overall shift of employment and revenue generation has been from the agricultural and extractive industries to the service sector, the overall scope of manufacturing activity has not declined significantly. This is especially true in the global economy, with manufacturing shifting to developing economies over time and expanding because of growth in global economic activity.

Service economies partially decouple material consumption from revenue generation, in the sense that total material requirements per unit gross domestic product decline in countries such as the United States as the economy evolves (Figure 3.1). However, such economies do not dematerialize completely. Every service—whether a fast food restaurant, a medical treatment, a retail store, or the Internet—requires a physical platform based on the use of materials and energy. Thus, although the patterns of materials use become much more complex in service-oriented economies, materials of all kinds remain foundational to economic evolution and the quality of life (Sidebar 3.1).

GLOBALIZATION OF THE ECONOMY

The international political structure also has an effect on material flows and it has been evolving as well. The relative simplicity of interna-

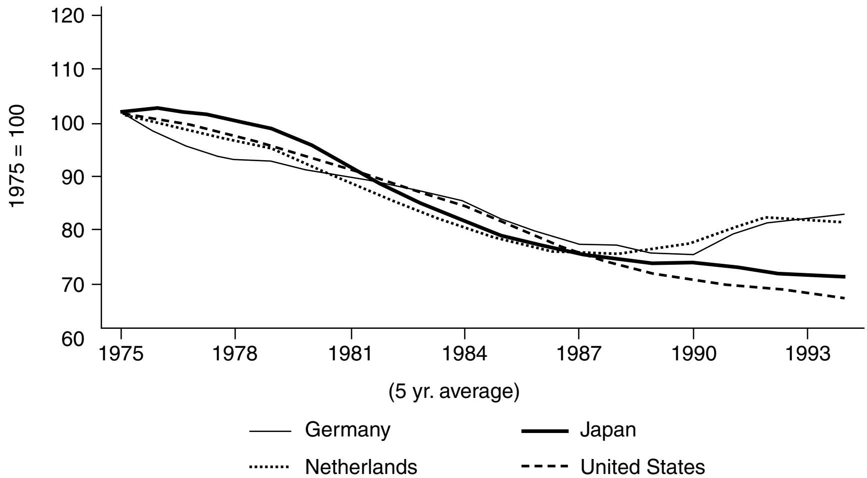


FIGURE 3.1 Overall material intensity (total material requirements per gross domestic product) index. SOURCE: Adriaanse et al., 1997. Copyright permission granted by World Resources Institute.

tional governance systems dominated by nation-states has given way to much more complicated networks of power, particularly in areas such as trade, human rights, and environment. The result has been a shift toward a more complex structure, including not just nation-states, but also multinational firms, nongovernmental organizations of all types, and communities, both traditional and, increasingly, based in cyberspace. This development has had several important implications for material use patterns. First, it increases the number of issues and stakeholders associated with material extraction, processing, and management. Whereas a mining firm previously had to deal only with the national government in a developing country where it operated for example, it may now find itself negotiating with local communities and developed-country human rights and environmental campaigners. Second, global markets may be affected by nongovernmental organizations' campaigns regarding a company's management of its products and waste streams in jurisdictions around the world. Many nongovernmental organizations focus on a "single issue." Thus, they may be concerned about only one dimension of corporate performance and ignore the economics of material extraction, processing, and management. The potential for adversarial relationships and conflict increases as the number of stakeholders increases. Material flows accounts cannot resolve the confusion of a more complex governance system, but they can help decrease the potential and scope for such conflict by providing an objective basis for dialogue.

SIDEBAR 3.1
The Role of Materials in Service Economies: Telecommunications

Modern economies are increasingly dominated by service, rather than manufacturing or materials production sectors, but that does not mean that material flows accounting is any less important in helping to support economic efficiency. To begin with, services are necessarily based on physical infrastructure, including buildings, manufactured products, or substances such as fuel used to provide the service. In telecommunications, for example, the technology platform consists of many different kinds of manufactured electronic products, linked together by transmission facilities. Economically, environmentally, and socially efficient design, manufacture and use of these artifacts depend directly on knowledge of the materials involved, as in the lead solder example discussed in sidebar 1.1. Analysis of the role of materials is more complicated when the entire telecommunications network is viewed holistically, because optimizing the economic, technical, environmental, and social performance of the network is a system function, not a component function. Physical networks are used, of course, to provide a variety of services, an even more complicated analytical challenge from a materials design perspective, but even at the level of service provision, material flows accounts have a role. Many telecommunications services provide functions that influence the demand for materials. In the case of corporate intranets, for example, publication of information in cyberspace rather than on paper reduces paper demand. Electronic billing enabled by telecommunications services can also dramatically reduce demand for paper bills. Research identifying opportunities and implications of such substitution of services for material use, and the role of material flows accounts in helping understand them, is in its infancy but, given the evolution of developed economies toward services, is an area deserving further study.

These trends illustrate the globalization of economic activity, which itself creates important needs for material flows accounts. Globalization is the process by which systems previously described by national or regional boundaries have become globally coupled and interconnected, creating more complexity. The implications of globalization for materials are significant. Most obviously for the United States, its complex economy has grown to rely heavily on material imports. The United States imports 100 percent of several commodities and significant proportions of other critical materials (Figure 1.2). These patterns of material use clearly suggest that any materials accounting methodology should extend beyond national boundaries to be truly systemic and ensure the capture of important information. Such material source data could, for example, indicate to firms or countries that, although absolute physical scarcity of a particular material is unlikely to be a short-term economic problem, the availability of important materials may be compromised by political or institutional factors.

This should not be surprising: in terms of commodities—from food to fuel to materials of various kinds—history indicates that shortages most often arise from institutional deficiencies and factors, rather than absolute scarcity. A classic example is the availability of minerals, where a particular mineral becomes scarce cyclically as the selling price and margin vary over time. With a higher price, the margin grows and so does exploration to expand reserves of the minerals and increase its availability. Thus, an important function of materials and energy information for firms and society as a whole is to provide the foundational data upon which material security and availability studies may be based (including, for example, identification of potential substitutes for materials controlled by possibly hostile governments). One of the reasons that DuPont uses material flows analysis is to avoid being significantly impacted by a supplier crisis (see Chapter 4) (J. Carberry, DuPont, personal communication, 2002). In this sense, material flows accounts are important mechanisms supporting the economic resiliency of firms and of the U.S. economy as a whole.

SUSTAINABLE DEVELOPMENT

There are social trends that are just as broad as the evolution of the service economy and that also urge the need for material flows accounts. Most obvious, perhaps, is the concept of sustainable development. This idea was brought to the world's attention by the World Commission on Environment and Development, also known as the Brundtland Commission, in 1987 in its report *Our Common Future* (World Commission on Environment and Development, 1987). There it was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." It represents an effort to integrate economic development with stewardship of natural resources, quality of the environment, and human equity, especially the right of poor countries to develop. Recent discussions in the United States, the Organization for Economic Cooperation and Development, the World Bank, and elsewhere relate sustainability to the maintenance or improvement of stocks of various forms of capital such as built infrastructure and facilities, productive capital, natural resources, and the quality of the environment. The idea of sustainability is important in many policy, environmental, and scientific communities. The value of material and energy flows information for supporting and adding substance to studies of sustainability across broad areas of economic activity is apparent. Indeed, it is difficult to see how any reasoned discussion of sustainability can take place in the absence of information regarding the stocks and flows of materials and energy within economies and natural systems. Importantly, as sustainability issues are addressed in the future, the full cost accounting of policy options should be considered, and material flows accounting, coupled with various derived indicators, will give insight on the impact of the options. Some policy makers indeed believe that the market will not operate correctly—and sustainability will not be achieved—until full cost accounting is achieved.

TECHNOLOGY EVOLUTION

As the above factors indicate, the modern world is far more complex than that of the late nineteenth century, when the United States first began gathering material flows data. Rates of change of technologies, industrial sectors, and economic structures are, if anything, increasing partially as a result of the autocatalytic effect of technological evolution. Such complexity obviously poses challenges to material and energy flows analysis methodologies—how, for example, should material flows data systems be designed to ensure that they are both up-to-date and reflective of technological evolution as it occurs? It also emphasizes the need for structured accounts for material and energy data, so that basic patterns of material and energy production, consumption, and disposal can be identified; the changes in those patterns tracked as technology changes; and that information, in turn, provided to numerous stakeholders—from corporations to nongovernmental organizations and governments—to inform and improve their decisions.

BIOGEOCHEMICAL CYCLES

More broadly, as a result of the Industrial Revolution and consequent technological, economic, and demographic evolution, the dynamics of most natural systems, such as the carbon and nitrogen cycles, the climate and hydrological cycles, and biological systems at many scales, are now increasingly impacted by human activity. Continued economic progress and stability of these human and natural systems will require the ability to better and more rationally engineer and manage them in a highly integrated fashion. It is apparent that rational action in such a complex environment, characterized by highly integrated and coevolving human and natural systems, requires a basic knowledge of the material patterns that underlie it. Without such knowledge it would be impossible to understand what the economic, social, and environmental impacts of various choices may be. This observation has methodological implications as well.

Most importantly, material and energy cannot in such a world be limited just to "human" or "natural" components of stocks and flows; they should encompass both. Moreover, beyond materials of economic interest to humans, material flows accounts should also embrace material systems that are perceived to be "non-human"—especially the four so-called *grand cycles*: nitrogen, carbon, sulfur, and phosphorus.

The connection among traditional ecology, industrial ecology, and material flows provides opportunities for holistic analyses of interactions that could lead to better public policy making, founded on strong multidisciplinary research and studies. Ecology is built on the premise that everything is connected to everything else. The biologist who ignores the connection between ecology and material flows is as short-sighted as the engineer that misses the connection. For example, the degradation of air, land, and water resources will never be fully understood or reversed unless the flow of materials impacting them is well understood, in both quantity and composition. Discovering and addressing the underlying cause of the decline of stratospheric ozone, for example, required an understanding of material flows. Limiting the exposure of children to lead required material flows analysis. Ultimately, addressing the solid waste problem will be dependent upon a much better understanding of material flows. Thus, public policy making based on linkages among material flows information with biological and physical information can be more robust and must necessarily be founded on multidisciplinary research in this area.

SUMMARY

The changing nature of economies, the complexity of products and services, the global nature of markets, the increasing human impact on natural cycles, and the international political structure have heavily impacted the magnitude and flows of materials, which have been evolving in complexity as well. These developments have had several important implications for material use patterns and have increased the number of issues and stakeholders. Moreover, the United States is dependent on other countries for 100 percent of several commodities and significant proportions of other critical materials. One potential important use of material flows accounting, therefore, is the identification of potential substitutes or the creation of stockpiles for materials controlled by possibly hostile governments.

The idea of sustainability is important in many policy, environmental, and scientific communities. Material and energy flows information is important for supporting and adding substance to studies of sustainability across broad areas of economic activity.

4

Material Flows Accounting: Uses and Usefulness

Material flows databases and analyses are already well established in a variety of U.S. government agencies. Material flows analyses at the plant, corporate, and national levels are also being done by private organizations. However, primarily because formal material flows accounts are not established in the United States, the value of material flows accounting is not widely recognized.

The following discussion highlights the current or potential value of material flows data and accounting, as well as the need to better understand material flows in a global society that progressively uses more materials. The examples discussed in this chapter are not intended to be inclusive but are intended to show the range for activities in government and private industry.

While it may seem obvious that good material flows analyses are dependent on quality data being captured and maintained in material flows accounts, the role for formal material flows accounts must still be clearly defined, as must the level of disaggregation necessary if the accounts are to properly serve the needs of society. The issue of disaggregation was addressed by the U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flow (2000, pp. 78-79), as follows:

> National-level information is useful for an overview and a sense of the trends, problems and opportunities in materials and energy flows. Information needed to support decision-making is most useful when disaggregated to a regional, local, industry sector or enterprise level. This level of detail in the gathering and analysis of data can be expensive but is

necessary to support informed decisions and more efficient use of energy and materials with less environmental degradation.

The reality is that the benefits of a problem- or issue-specific material flows analysis appear to be much better documented than the benefits of formal material flows accounts, especially at the national level. This chapter therefore takes a more structured look at typical uses of material flows accounting and analysis, with a focus on the value of formal accounts. What emerges is a need, not for expansive new data collection programs, but for the development of a carefully structured material flows accounting framework that can accept and integrate existing and future data streams.

MATERIAL FLOWS INFORMATION IN THE PRIVATE SECTOR

Material flows tracking, rather than accounting, is used, or could be used, in the private sector for various purposes, ranging from simple plant-level mass balance approaches to improve materials efficiency or set corporate strategies on investment and emissions, to more complex assessments of the availability of critical resources or manufactured inputs at a national and even international scale. Material flows information can also be used to better understand the material makeup of products and related flows, especially for recycling and reuse. Examples of material flows tracking in the private sector, are discussed below. Two consistent themes emerge from this information: (1) materials flows accounts should be based on systems thinking, whether the system is small or large; and (2) the availability of reliable data is very important, irrespective of whether the focus is on narrow corporate concerns, an entire sector, or national and international flows.

DuPont

DuPont uses material flows tracking and analyses to assess materials effectiveness in the sense of the relationship of mass and/or energy inputs to functional effectiveness and materials efficiency (J. Carberry, DuPont, personal communication, 2002). Material flows tracking is also used to follow the recycling of durable materials, especially steel, lead, and aluminum, and to improve the utilization of all materials, where waste from other processes, companies, or industries might become the raw material for a process of interest.

A particularly notable aspect of material flows tracking at the corporate and international level is DuPont's assessment of its dependence on specific suppliers for critical inputs and its consequent vulnerability to disruptions in the supply chain. On one occasion, the company's entire U.S. production process would have been stopped after a catastrophic accident that destroyed the facilities of the sole international supplier of a critical input. Fortunately, DuPont had already identified its material flows dependence and developed an alternative formulation that could be brought into production quickly.

This kind of highly quantitative information is valuable from an industry perspective, but its application to societal materials flows analysis may be limited. Perhaps its leading contribution would be to point to the potential value of a limited amount of valid, appropriate data as the basis for good analysis and action (J. Carberry, DuPont, personal communication, 2002).

Alcoa

Alcoa maintains an extensive, on-line, real-time system to track performance data, from which baselines are established and targets set at both the local and the corporate levels (P. Atkins, Alcoa, personal communication, 2002). Equally critical is the need to look for more efficient ways to use aluminum, other materials, and energy throughout the life cycle, with greater emphasis on recycling (P. Atkins, Alcoa, personal communication, 2002). Life-cycle assessment (Sidebar 4.1) is therefore an important tool that can give holistic, quantitative summaries of environmental performance in terms of resources consumed and emissions to the environment, considering the entire value chain (i.e., supply, production, customers, product use, and recycling).

From the industry's perspective, it must create a better process for valuing natural resources, improve the integration of life-cycle assessment and material flows approaches, improve statistics on recycled materials, and seek worldwide integration of data (P. Atkins, Alcoa, personal communications, 2002). Accordingly, in 2001, the International Aluminum Institute set the goal of performing a comprehensive, peer-reviewed, worldwide inventory on all significant air emissions, resource consumption, waste generation, and water pollutants associated with primary and secondary aluminum.

Vulcan Materials Company

Vulcan Materials Company is an example of a private company that has developed and maintains an in-house material flows database at both regional and national levels (D. Meyer, Vulcan Materials Company, personal communication, 2002). The database, which tracks aggregate and cement operations in the United States for the last three decades, is be-

SIDEBAR 4.1
Life-Cycle Assessment

Life-cycle assessment is formally defined as "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 1997). It has been widely accepted within the environmental research community as a good basis on which to compare alternative materials, components, and services.

Using life-cycle assessment, the environmental performance of products or processes is properly examined on a system-wide basis, considering a broad range of environmental inputs and outputs. Life-cycle inventory analysis, the cornerstone of life-cycle assessment, involves the quantification of environmentally relevant flows associated with any process, including materials and resources consumed and emissions to air, land, and water. Life-cycle inventory data are used to characterize emissions and develop various eco-indicators, with the validity of any measure or indicator absolutely dependent on the validity of the underlying data. For example, a measure of global warming potential will be only as good as the underlying data on carbon dioxide, methane, and nitrous oxide emissions.

Life-cycle assessment differs from material flows accounting in that it focuses on the level of specific products throughout their life cycle, including the supporting supply chains. It may benefit directly from the existence of material flows accounts.

coming increasing more important as the aggregates industry evolves from a primarily local, truck-dominated industry to a multimode (i.e., rail and water), regional, and even multinational industry.

The company's database contains a large amount of information, including the number of quarries and companies and their production levels. By considering the production in a geographical area relative to market demand, Vulcan Materials Company can determine where there are deficits, balances, or surpluses in production (D. Meyer, Vulcan Materials Company, personal communication, 2002). For example, within the last 20 years, the number of balanced counties (i.e., where the demand for aggregates roughly equals the rate of aggregate production within the county) dropped by approximately 50 percent. Of the 3,073 counties tracked in the database, only 195 went from a balanced state to a surplus, while 482 counties went from a balanced state to a deficit (Figure 4.1). Moreover, aggregates are now being imported to the East Coast from Canada and the Caribbean—a remarkable development given the supposed abundance and relative low cost of this critical building and construction material.

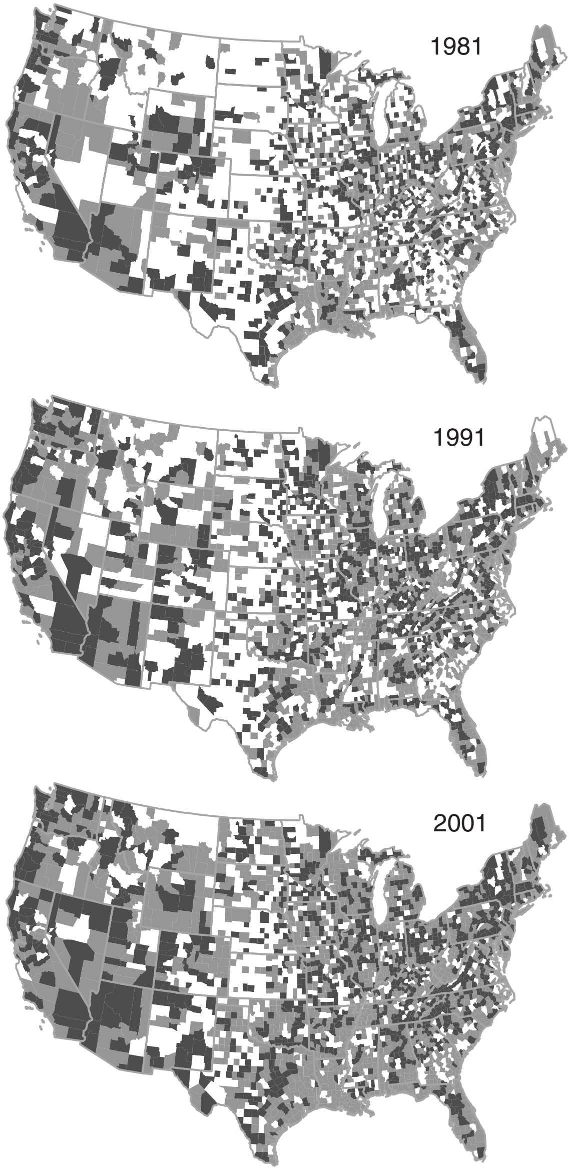


FIGURE 4.1 Determination of counties in which there are deficits in production (black), balances (white), or surpluses (grey). During the last 20 years, the number of counties in which the demand for aggregates equaled the output within the county dropped by 50 percent. SOURCE: D. Meyer, Vulcan Materials Company, personal communication, 2002. Copyright permission granted by Vulcan Materials Company.

This is an excellent example of the value of a material flows database; it has strategic implications for optimizing resource processing and use options, for optimizing delivery and therefore transportation-related energy use and emissions, for private investment decisions, and for estimating municipal and regional building costs. The value of the database is particularly notable in light of the enormous growth in the importance of sand, gravel, and aggregates relative to other material flows as depicted in Figure 1.1.

Recycling Industries

The Institute of Scrap Recycling Industries is a private, for-profit recycling group consisting of approximately 1,300 companies, with a primary interest in material flows accounting for waste streams. Noranda, one of the world's largest producers of zinc and nickel and a significant producer of other metals, is a major recycler of copper, nickel, and other precious metals. Both organizations have specific insights regarding the value of material flows accounting, as well as concerns about its implementation.

The Institute of Scrap Recycling Industries believes that by tracking the types and quantities of materials that end up in landfills, it may be possible to use these materials at a later date, thereby providing major public benefits such as reducing landfill disposal and offsetting demand for virgin materials (T. Tyler, Institute of Scrap Recycling Industries, personal communications, 2002). Such tracking and targeting of materials for recycling could be a long-term benefit of material flows accounting. General data are available on what materials on average are consistent with class IV landfills (i.e., those landfills deemed to have limited environmental impact). Getting accurate measurements of materials in any particular class IV landfill would be difficult, costly, and time consuming. However, obtaining this information from a commercial landfill (i.e., those landfills handling commercial, industrial, and construction wastes) might be less difficult, costly and time consuming. Segregation of discarded waste materials is an important consideration. Using materials from landfills would be challenging because of potential contamination issues, and the cost of recovering the materials and then recapping the landfill might be prohibitive. However, the cost of segregating materials at landfills will have to be considered in relation to the ultimate benefits for society. The committee notes that it is difficult to find accurate recycling data, especially from smaller companies.

Recycling often involves complex mixes of materials, some with significant potential impacts on the environment and public health. For example, there are approximately 250 million mercury switches in U.S. vehicles (Institute of Scrap Recycling Industries, 2001). Used to turn on convenience lights in trunks and hoods, each switch is about the size of a dime and contains about 1 gram of mercury. The problem arises because the small size of the switches precludes their easy removal during scrap processing, while the sheer number of switches represents a significant environmental risk. Material flows accounting could prove useful in understanding the extent of a serious, impending environmental impact and also provide insight into how complex the problem will be to deal with effectively.

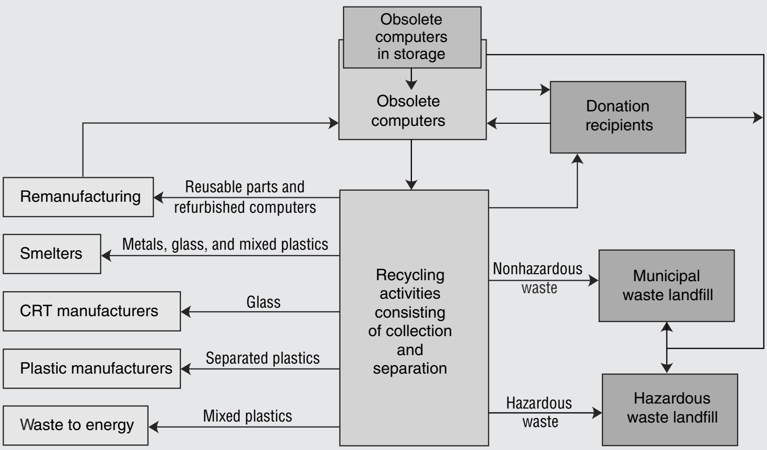
Recyclers also have difficulty keeping up with rapidly changing markets. For example, some packaging such as the aseptic packaging used for juice boxes, which is relatively new to the market, cannot be recycled economically. For these and other reasons, the Institute of Scrap Recycling Industries believes that the collection of accurate recycling data is imperative given the important role that recycling plays in today's economy, and its even greater role in the future as sustainability issues are addressed (T. Tyler, Institute of Scrap Recycling Industries, personal communication, 2002). It is notable that the Japanese, in framing their approach to material flows accounting, decided that recycling would be tracked. In contrast, the European Union has decided not to track recycling data in a major way; rather, it has proposed the use of subaccounts as data become available.

In 1984, Noranda Inc. began processing small amounts of electronic scrap and by 1999, had the largest electronic recycling plant in North America (Reid, 1999; USGS, 2001). Recycled materials are considered an important feedstock for its smelters (Sidebar 4.2). For Noranda, recycling is not limited by technology or by the demand for recycled materials, but by the supply of recycled materials and competition with primary metals; and thus, the accounting of recyclable materials will play an ever-increasing role for companies such as Noranda.

Noranda embraces the use of material flows approaches to improve product design, and to facilitate technological innovation so as to increase the efficiency of resource use, to better manage waste, and to make more effective policy decisions (L. Surges, Noranda, Canada, personal communication, 2002). However, it cites two basic issues that have to be addressed—the potential scarcity of materials and the environmental impacts of processes, uses, and disposal of materials—and would like to see further efforts to develop consistent standardized information for accounting of resources and the impact of resource use. In the company's view, there are a number of complications that must be considered in developing an effective material flows accounting system. Stocks and flows must be considered, but some relevant stocks are difficult to quantify while others are unknown (e.g., the amount of recoverable copper in an auto-

SIDEBAR 4.2
Recycling of Computers

As an example of how complex and significant the recycling of materials can be, obsolete computers contain substantial amounts of recoverable materials including metals (aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, gallium, gold, iron, lead, manganese, mercury, palladium, platinum, selenium, silver, and zinc), glass, and plastics. For example, 1 metric ton of electronic scrap from personal computers contains more gold than that recovered from 17 metric tons of gold ore. The number of obsolete computers increases every year because computers are becoming a more important part of all aspects of our lives and because consumers are upgrading their systems frequently. Computers and other electronic devices represent a large resource of potentially recoverable materials. In 1998, 52,300 metric tons of material were recovered by electronics recyclers in the United States. This included 13,200 metric tons of glass and 19,900 metric tons of steel. A generalized material flows diagram for obsolete computers and their components is shown below.



SOURCE: USGS, 2001.

mobile salvage yard). Natural sources, sinks, and fluxes, as well as imports, exports, and inventory changes, must be quantified to place stocks and flows in context. Materials sent for disposal in landfills may or may not be recycled in the future and may or may not represent a permanent loss from the materials system; thus, such material flows should not necessarily be considered releases to the environment, but rather in many cases an augmentation of stocks of materials. This last point relates to the role of recycling in material flows accounting.

U.S. Construction Industry

Building-related activities use materials, energy, and water and generate municipal solid waste. An input-output study of nearly 500 sectors in the U.S. economy found that the construction sector produces the most CO_2 emissions through the manufacture, transport, and use of materials (Norris, 1998). At about 300 million metric tons, this sector creates more upstream fossil fuel CO_2 emissions than the direct total fossil fuel CO_2 emissions of all U.S., state, and local government electric utilities.

This sector is also characterized by heavy use of aggregates, metals and alloys (e.g., copper, zinc, aluminum, and steel), glass, and wood, with material choices made largely on the basis of cost, availability, and performance rather than environmental impacts. In addition, the ultimate disposition of these building materials is rarely taken into consideration during the initial planning and design phase of a building, and it is general industry practice to order 10 to 25 percent excess building materials in case of weather damage or breakage during shipment. Only recently has a level of awareness developed of the importance of waste streams from construction sites as they relate to local landfill and site stockpiling issues.

The Leadership in Energy and Environmental Design assessment system (LEED), a green building rating system developed by the United States Green Building Council (USGBC), is intended to foster increased awareness of these and other issues and to encourage and reward improved practices (for more information see, USGBC, 2003). In the relatively short time since its introduction, it has become the most widely used U.S. environmental evaluation system in both the public and the private sectors. Work is now under way to determine how the system can be improved by including more quantitative life-cycle assessment techniques (Sidebar 4.1). That work, in turn, will benefit from the existence of material flows accounts.

MATERIAL FLOWS ACCOUNTING IN THE PUBLIC SECTOR AND NONGOVERNMENTAL ORGANIZATIONS

This section focuses on the uses and usefulness of material flows data at the multinational, national, state, and municipal levels.

Multinational Material Flows Accounting and Derived Indicators

The World Resources Institute, in cooperation with other international institutions, compiled two reports on material flows accounts and derived indicators for a number of national economies (Adriaanse et al., 1997; Matthews et al., 2000) (Sidebar 4.3). Presenting a conceptual model of the complete material cycle in the industrial economy through material flows analyses, these studies indicated that waste generation continues to increase despite increased efficiencies in the industrial economies; that a large proportion (50 to 75 percent) of annual resource inputs to industrial economies returns to the environment as wastes within a year; that outputs of many potentially harmful materials are increasing, notwithstanding the successful stabilization or reduction of others; and that fossil energy-based outputs dominate output flows in all industrial countries.

Based on its studies, the World Resources Institute concluded that physical accounts are needed because the knowledge of resource use and waste outputs is surprisingly limited. National economic accounts do not include activities for getting natural resources that are not bought or sold, even though there might be environmental consequences of using these resources. With the knowledge that current economic accounts and environmental statistics are not adequate for tracking flows into and out of the economy, there is concern that society might lose sight of some materials in the course of processing and entirely miss other major flows, such as soil erosion from cultivated fields, that do not enter the economy (Adriaanse et al., 1997). Focusing on national and multinational levels, the World Resources Institute's overarching conclusion is that targeted policies will be needed to accelerate the trend toward dematerialization and to encourage the substitution of benign materials for those that are environmentally harmful.

The European Union member states have collaborated recently to begin standardizing the principles and practice of material flows accounting. As noted in Chapter 2, agreed-upon definitions, a framework for the accounts structure, guiding principles, and trends from analyses of member states' national accounts are discussed in detail in the Eurostat guidelines document (Eurostat, 2001). The development of key, derived input, consumption, and output indicators is a primary purpose of the accounts.

The guidelines document seizes this opportunity, and defines and interprets various indicators relative to environmental impacts.

Developments in Japan have been slower than in Europe. Although Japan is still in the preliminary stage of development of national material flows accounts, it has more than 10 years of history in material flows analysis for environmental accounting. In the early 1990s, Japan sanctioned a pilot study on natural resource accounting for forests, and material balance analyses were begun in 1992 for a report on the *quality of the environment* (Moriguchi, 2002). Japanese researchers have also participated in the aforementioned international comparison studies on material flows (Adriaanse et al., 1997; Matthews et al., 2000) and have done a detailed material flows accounting white paper on a recycling-based society (Y. Moriguchi, National Institute for Environmental Studies, Japan, personal communication, 2002). Material flows accounts are not yet institutionalized as a routine operation by a statistical agency, but Japan is progressing in that direction. One example of the usefulness of material flows accounting in Japan is highlighted in Sidebar 4.4.

U.S. National Accounting

Although not formally defined based on a national or international standard system, there are several examples of national material flows accounting and analysis documents generated by the U.S. Geological Survey, the Environmental Protection Agency and other agencies. The benefits of this work and of ongoing programs are discussed in many of the referenced sources and, in some cases, have been mentioned earlier in this report. For example, high levels of silver were detected in San Francisco Bay in the 1970s. A follow-up study found that the problem was caused by product- and location-specific material flows in waste streams. Analysis ultimately lead to an understanding of the potential value of material flows accounts at a national level (Kimbrough et al., 1996). Had formal national-level accounts been in place, they would have been the first logical step in assessing the high levels of silver in San Francisco Bay, making it possible to quickly answer questions about silver flows in the local economy. Rejeski (1998), after summarizing the lessons learned from the silver case and two other scenarios (lead and arsenic), muses that these cases "point to a future where intelligent environmental policy will increasingly depend on our ability to understand material leakages, substitutions, and shifts, and to understand these systemically across space and time."

SIDEBAR 4.3
Noting Trends in Material Flows in Industrial Economies

The Weight of Nations: Material Outflows from Industrial Economies (Matthews et al., 2000) demonstrates the use of national physical accounts for five countries in marking trends in total domestic output from 1975 to 1996. Total domestic output is defined as the aggregate measure of domestic processed output (material outflows from the economy) plus domestic hidden flows (those that do not enter the economy). The graph at right, which includes the trends with annual data indexed to 1975 flow levels, shows a relatively stable pattern of total domestic outputs over the 20-year period, with few exceptions. Notably, Japan's index rose by 19 percent over the period, primarily reflecting an increase in hidden flows associated with publicly funded construction programs. The impact of reunification in Germany is also clearly shown, with an index decline occurring at a comparatively rapid rate since 1991.

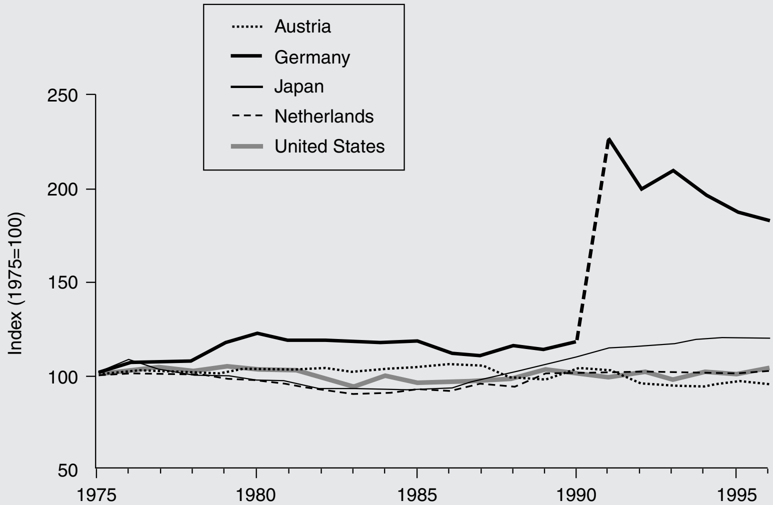
The aggregate data from account analyses can also give comparative numbers on the size of national economies and the magnitude of domestic processed output, as well as total domestic output. In the document analyses, for example, compared to Austria, the Netherlands, Germany, and Japan, the United States has a disproportionately large total domestic output for the relative size of its economy. This phenomenon reflects the magnitude of hidden flows associated with domestic processed output.

All of the countries studied show a marked improvement in material outflow intensity (domestic processed output per gross domestic product) over the 20-year period, a measure of economic efficiency, as domestic material output increased substantially. These measures demonstrate well the use and usefulness of formal national-level material flows accounts and accounting in monitoring national trends.

National Security Implications

The previously noted national security implications of material flows accounting deserve special attention. Figure 1.2 provides a striking illustration of the extent to which the United States is 100 percent dependent on foreign sources for a wide range of non-fuel commodities and more than 50 percent dependent on such sources for many more materials.

A national material flows accounting system, and the resulting flows accounts, would give national security strategists a much better picture of the sources and distribution routes of materials critical to the U.S. economy. For example, more than 75 percent of some major metals used in new technology development or in products conventionally manufactured in the United States are imported (Wagner, 2002). As cases in point,



Trends in total domestic output for the period 1975-1996. SOURCE: Matthews et al., 2000. Copyright permission granted by World Resources Institute.

SOURCE: Matthews et al., 2000.

palladium and platinum, used in photovoltaic and fuel cells for clean power generation and in catalytic converters, respectively, come almost exclusively from Russia and South Africa (Wagner, 2002).

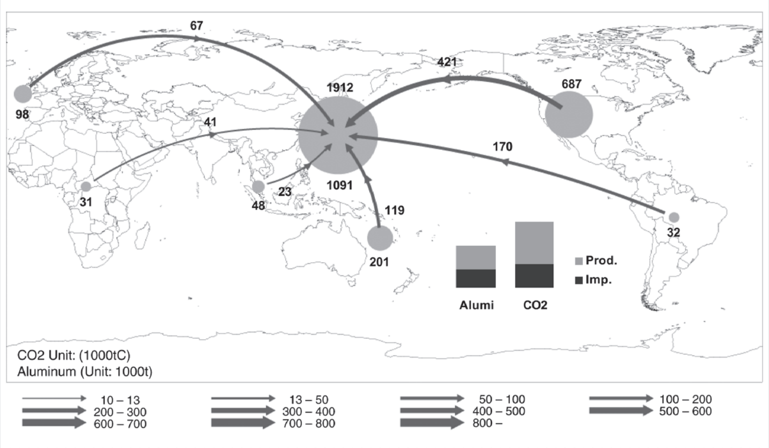
State Material Flows Accounting

As noted in Chapter 2, the State of New Jersey has been tracking the movement of toxic materials since the mid-1990s, not only as production wastes, but also in transport to and from factories, stored on the plant site, and leaving in products or as products (Dorfman and Wise, 1997) (Sidebar 2.1). Although this information is gathered at the plant scale, the results can be used for statewide policy making, and the program stands as an

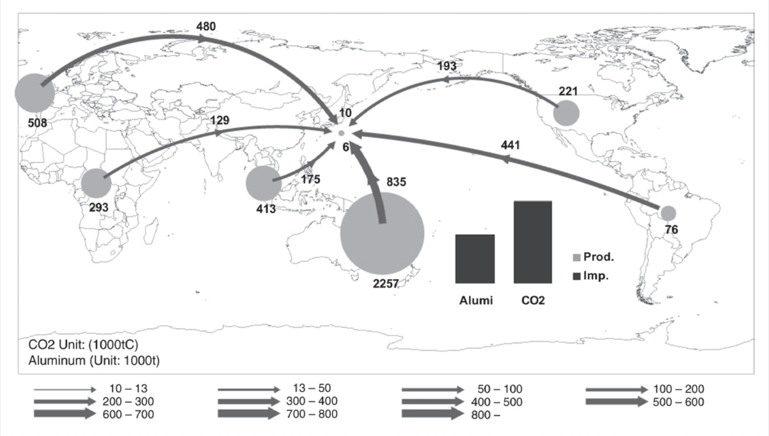
SIDEBAR 4.4
Global Material Flows Accounting: Japanese Dependence on Aluminum Imports

An interesting perspective on global material flows is presented in the following two figures, which depict sequentially Japan's growing dependence on imported aluminum from 1980 to 2000. The first figure shows the flows of primary aluminum, in thousand metric tons, imported by Japan in 1980, using arrows with magnitudes related to line thickness. It also shows flows of carbon dioxide production associated with the extraction and processing of alumninum ore, with the sizes of circles representing the relative magnitudes of releases at the indicated locations. The bar graphs indicate the balance of production and CO_2 generation between domestic activities and those that take place in regions from which Japan imported aluminum. The second figure shows the flows in 2000 and indicates a tremendous reduction of primary aluminum production and CO_2 generation in Japan, with tremendous increases in exporting countries.

SOURCE: Unpublished materials by Y. Moriguchi, based on Moriguchi, 2003.



Domestic production and import of primary aluminum, and CO_2 emissions associated with them for 1980.



Domestic production and import of primary aluminum, and CO_2 emissions associated with them for 2000.

excellent example of substance-specific material flows accounting at a regional level. The benefits of the program to date have been well documented. For example, New Jersey found three unique ways in which the material accounting data are useful: first, the data provide the preliminary information needed for assessing worker and community exposures because they identify which toxic chemicals are used at industrial facilities and in what quantities; second, the data provide a means of measuring the results of source reduction activities by assessing the efficiency with which companies are using chemicals; and third, the data provide a means for regulators to verify the accuracy of chemical quantities reported to the Toxics Release Inventory. Notably, although the use of toxic chemicals in general increased in New Jersey between 1991 and 1994, the use of particularly hazardous chemicals dropped by about 5 percent (down 13.3 billion pounds). Likewise, even though the non-product output (material used less, material consumed less, material shipped as or in product) increased from 1991 to 1994, facilities reported the highest level of source reduction in 1993. It should also be noted that there are some concerns that the New Jersey database is not readily available to the public, is difficult to use, and is not complete (Dorfman and Wise, 1997).

It is clear that much more could be gained from this groundbreaking program if there were a framework for linking the plant-level flows within the state and across state boundaries to other states or regions. In the context of the definitions provided in Chapter 2, there is the potential to extend this database to the level of a state physical input-output table, which in turn could be made part of a national physical input-output table by including cross-border flows.

Municipal Accounting Applications

An overview of selected public sector activities, from the municipal to the national levels, further develops the case for creation of a systematic material flows accounting framework. Whether the physical asset is a bridge, a street, or a building, there are enormous material flows implications in the life cycle of municipal assets. For example, a bridge needs periodic painting to maintain its structural integrity, which means containment to protect waterways below from lead, the erection of steel scaffolding, and concern about the chemical makeup of the paint. Similarly, black asphalt roofs have to be replaced about every 20 years with a full range of material and energy flows, along with their environmental implications. For any municipality of reasonable size, this is a continuous process. In many cases, there are better alternatives to conventional practice, but it is inordinately difficult to undertake sufficient research at the municipal level to challenge entrenched interests and insist on a change in the use of materials. A material flows accounting system could potentially provide powerful corroborating information in support of decision-making regarding substitution of materials and the diminution of environmental impacts.

In general, the ability to undertake full accounting of materials could more comprehensively illustrate the value and tradeoffs of asset design, construction, and maintenance decisions at the municipal scale. Geographic information systems are increasingly being used in municipalities to satisfy government financial accounting standards and to provide information to enhance decision-making regarding the spatial relationships of public infrastructure and physical assets in geographic areas. (Fitch et al., 2001). Systematic material flows accounting, linked with municipal geographic information systems, would offer yet another tool for tracking material flows associated with these assets and would help local governments achieve the greatest and best use of available physical and financial resources.

SUMMARY AND FINDINGS

The primary purpose of a material flows accounting system is to create, develop, and maintain a formally structured, common database system that integrates, consistently, existing material flows data from government, business, and public sources such that they may be used, through analyses and linkages with other databases, to provide insights on material flows in physical and/or economic systems and permit more holistic, robust public policy decisions based on the integration of economic, public health, and environmental considerations. The activity of informing public policy generally involves the creation of various types of indicators of the intensity of material flows on the input and output side related to the impact on the environment, but could also include their relationships to economic, quality-of-life, and public health measures.

Uses of material flows data for different types of analyses exist at many levels in the United States and abroad. The analyses demonstrate the usefulness of materials flows data, and some in the international community have pointed to the need for, and usefulness of, material flows accounts capable of embracing data from the global to the local levels.

From the above descriptions it can be seen that different sectors of industry track the flows of materials important to their business, including recycled materials. They do not use a formally defined standard system of accounts for this purpose. The data that are collected obviously allow companies to improve their business performances or remove uncertainties regarding materials availability, thereby proving useful to them. Such data could be available for incorporation into a national system of material flows accounts but would have to be converted for use in a common database.

Generally, the situation is similar for federal and state government agencies in the United States, although for different purposes than industry. For example, the EPA and the state of New Jersey track chemicals designated as toxic or hazardous, but not by using a formal material flows accounting system. New Jersey focuses on achieving mass balances at the chemical facility level, whereas EPA focuses on estimating the amounts of chemicals flowing into the environment.

The only formally defined systems of material flows accounts exist in European Union (EU) member states and in Japan. Material flows accounting does not play a prominent role in Japan yet, but several EU member states use it regularly. The European Union has converged on a union-wide standard for a material flows accounting system, that represents the most visible, formal standard at this time.

The committee notes, from the examples cited, that such material flows databases could be used to accomplish the following:

- Generate periodic reports on consumption rates of natural resources and their efficiency of use to improve the management of these resources.
- Track individual materials and product-related multiple materials that may impact natural and human systems to allow action to reduce negative impacts and identify the need to find alternative materials.
- Indicate periodically the potential implications, including trends, of materials use on natural and human systems to raise awareness and stimulate improvements in management.

The committee notes that the existence of a formal economy-wide material flows accounting system and a national physical input-output table would likely provide a range of benefits, including the following:

- Federal and state agencies would gain better information on the sources and uses of the mineral and renewable resources within their responsibilities.
- In the pursuit of continuous improvement of economic and environmental performances, corporations would have better information about current and potential supplies of the materials they use, about potential positive and negative environmental impacts of these materials, and about substitutes that could be used to supplant undesirable materials in their systems and processes.

- Users would be able to track sources, flows, and dispositions of materials to determine more effective strategies for improving environmental and economic performance as well as efficiency of resource use.
- National security strategists would have better data on the sources of materials critical to the U.S. economy and to national security—from energy materials, to rare metals, to widely used material resources.

The committee concludes that analyses using material flows data have already proven useful. However, the data are not being used as effectively as they could be if there were a consistent framework and system to collect, analyze, and distribute the information routinely and to link data at various levels. *The committee concludes that the establishment of material flows accounts and their use in analyses will improve public policy making.* As noted in Chapter 2, proper material flows accounting, like financial accounting, requires the use of a standardized structure and specified principles. **Therefore, the committee recommends that a structured material flows accounting framework that can accept and integrate existing and future data be established.**

5

Material Flows Information in the United States

This chapter describes the history of data gathering on material flows and the current public data sources for material flows in the United States. The chapter also discusses gaps in data that must be addressed if an ultimate goal of sound public policy making is to be achieved through implementation of a system of national material flows accounts.

Humans have processed and used materials since the dawn of civilization. For most of this time, small populations and low levels of technology meant that rates of materials extraction, use, and disposal were low. The situation changed significantly as the Industrial Revolution began. In the late nineteenth century, the tracking of sources of materials to feed economic growth in the United States became important; then, in the latter half of the twentieth century materials use exploded (Figure 1.1).

EVOLUTION OF MATERIALS DATA

In 1910, after the establishment of the U.S. Bureau of Mines, the statistical work on metals and minerals that was begun by the U.S. Geological Survey was transferred to the new bureau. The primary purpose of the early statistical accounts of mineral and metal reserves, production, consumption, and trade was to satisfy the need for information on materials for commerce and for national security, the latter leading to the establishment of strategic stockpiles. Early data on uses of scrap iron and steel were expanded to include nonferrous metals. From the early decades of the twentieth century, levels of metals recycling were tracked. Until the Department of Energy and its Energy Information Administration were established in 1977, the Bureau of Mines also provided information on oil, gas, and coal, not only for energy purposes, but also for the production of materials such as asphalt, tar, and lubricants from these raw materials. Throughout most of the century the attention was exclusively on minerals and mineral fuels.

In the late 1980s, the U.S. Bureau of Mines began an analysis of factors affecting competition among materials, including the use of plastics as substitutes for metals. This work led to a broadening of the scope of research to include all non-food and non-fuel materials. This era saw the initiation of a series of groundbreaking publications that examined the entire life cycle of materials used for physical goods and structure (USBM, 1989, 1990, 1991). The work also began to consider the environmental implications of the extraction, processing, production, use, and ultimate fate of these materials. Pioneering efforts included the quantification of hidden flows (such as the gangue portion of ore) associated with the flows of commodities and the identification of environmental releases from commodity flows.

To achieve a historical perspective, the magnitude of physical material flows by weight, volume, and value was examined for the entire twentieth century (expanding on work by Spencer, 1978). These data were then compared with changes in the gross domestic product and population during the century to assess how the use of specific materials waxed and waned during that period and whether decoupling with respect to population and gross domestic product was in fact taking place. To obtain a global perspective, the growth of physical material flows in the United States was compared to total global flows, and the degree to which long-term trends were sustainable was discussed.

In its last years, the Bureau of Mines translated its national efforts into a regional material flows analysis, as it did—for example—for the Council of Great Lakes Governors (unpublished study by U.S. Bureau of Mines). This study, conducted as part of the Great Lakes Recycle Program, examined commodity flows to identify how regional procurement policies of state and local governments could be used to effect changes in flows that could reduce environmental impacts, increase recycling, and provide increased inner city employment. This work led to the development of new techniques for using economic data to quantify specific material flows, principally of paper.

The Bureau of Mines also began material balance studies on several minerals and metals (e.g., Llewellyn, 1992). These studies created an inventory of the location of all of a specified material mined in modern times. The balances characterized how much metal is embedded in products or infrastructure currently in use, in stockpiles, or in landfills and gave an estimate of the total thus far dissipated into the environment.

In 1995, when the U.S. Bureau of Mines was closed, the minerals information functions were moved back to the U.S. Geological Survey, where they are continued today. The historical work on materials clearly demonstrated the importance of accurate and complete information on flows of minerals and metals. On May 4, 1994, seventeen Members of Congress signed a letter to the then Chairman, House subcommittee on Interior regarding the data from the U.S. Bureau of Mines: "The Bureau of Mines is providing vital analytical assistance to the Governors of the Eight Great Lake States… it is an innovative program that has generated much enthusiasm among the state government and has helped make great advances in the area of waste disposal and reuse."

Elsewhere in this report the example is given of AT&T using the same material flow information to avoid making a costly error in designing an electronic component with metals not available in sufficient quantities. In a letter to then Secretary Bruce Babbitt, Carol Witner of AT&T stated, "With the exception of the Bureau of Mines report, existing data on materials stocks and flows are generally scanty and of poor quality, thus limiting the ability of private firms to improve their environmental performance by choosing environmentally preferable materials."

The significance of these "testimonials" is that they were generated as the Congress and Department of the Interior decided to close the Bureau of Mines. The support for the material flow data lead to the preservation of more than 180 positions to maintain that vital information function back at the USGS. The same rationale exists today for the maintenance and expansion of the data and the institutional capacity to generate it.

The existing data historically available on metals and minerals from the U.S. Geological Survey and the U.S. Bureau of Mines provided the foundation that made useful work possible, and it also served to highlight the public domain data deficiencies with other commodity flows such as petrochemical products and compounds of chlorine.

Similar evolution of material tracking occurred at other government agencies (e.g., the U.S. Environmental Protection Agency). With the development of the Toxics Release Inventory in 1987 (established under the Emergency Planning and Community Right-to-Know Act of 1986 [42 U.S.C. § 11001 et seq.]), the Environmental Protection Agency began an evolution toward easily accessible data on releases to the environment, integrated into individual accounts for specific industrial facilities. The available data include accounts with air permit data, water permit data, waste generation rates, and environmental discharge data that are searchable by facility, industrial sector, or geographical region. These examples of the evolution of material tracking data provide evidence of sophisticated and useful data sets, evolving to meet changing needs.

CURRENT DATA SOURCES

At the national level in the United States, there are currently no regularly published, integrated data sets or material flows accounts that show total material production, use, and waste flows. Parts of this information are found in a variety of places because, historically, federal agencies have maintained data series on materials related to their organizational mission and responsibilities. No single federal agency has responsibility for all material flows data or accounts, but the U.S. Bureau of Mines and now the U.S. Geological Survey report on most raw materials. Minerals including construction materials and metals account for more than 90 percent by weight of non-food, non-fuel materials use in the United States (U.S. Interagency Working Group on Industrial Ecology Material and Energy Flow, 2000). The best sources of information on production and consumption of these materials, published annually by the U.S. Geological Survey, are the Mineral Commodity Summaries (e.g., USGS, 2003a) and the Minerals Yearbook (e.g., USGS, 2002b), which is comprised of multiple volumes on Metals and Minerals (Volume I), Area Reports: Domestic (Volume II), and Area Reports: International (Volume III). The reports give statistical summaries, describe trends for commodities, and explain survey methods. Supporting the development of these reports, companies voluntarily supply proprietary data with the understanding that these data will remain confidential (Sidebar 5.1). The published aggregated data show minerals and metals production and uses by sector, mineral and metal reserves, and often data on levels of recycling. The U.S. Geological Survey also publishes bulletins on the material flows of individual commodities and, occasionally, on total material flows for the entire United States using data from federal agencies and other sources (e.g., Wilburn and Goonan, 1998; Brown et al., 2000).

The U.S. Forest Service periodically provides statistical data on lumber, composite board products, and pulp and paper (Howard, 1997). Information in these reports is collected from industry trade organizations as well as from government agencies. The report data are intended for use by anyone with interest in the wood industry, and the focus is on technological change over the years examined (e.g., the shift from the use of plywood to the use of oriented strand wood in structural panels).

The National Agricultural Statistics Service of the U.S. Department of Agriculture produces annual statistics on cotton and other fibers, non-edible oils, and other agricultural materials (USDA, 2003). These data serve as a reference collection for agricultural production, supplies, consumption, facilities, costs, and returns. The Department of Agriculture collects and compiles the majority of these data.

First the U.S. Bureau of Mines and then since the 1970s the Energy Information Administration of the Department of Energy have served as

SIDEBAR 5.1
Proprietary Data and Data Aggregation

The U.S. Geological Survey relies on the voluntary cooperation of the U.S. mining industry to provide the mineral data contained in its various publications (e.g., Minerals Yearbook). The U.S. Geological Survey gets a strong response to its survey request—greater than the 75 percent response rate stipulated as acceptable by the Office of Management and Budget. In order to maintain its close partnership with industry, the U.S. Geological Survey respects the proprietary nature of data obtained from individual companies by aggregating the data. To ensure that proprietary rights are not violated, the U.S. Geological Survey analyzes each of the aggregated statistics to determine if the data reported by an individual company can be deduced from the aggregated statistics. If proprietary data could be deduced from these statistics, the data are not reported. Instead, a "W" is reported, indicating that the data were withheld. Similar data aggregation methods are used for census and public health data to protect the proprietary nature of the data.

SOURCE: Mlynarski, 2000.

the source of data on quantities of oil, gas, and coal for both energy and non-fuel products such as asphalt, lubricants, and plastics. This information is currently published in the Annual Energy Review (e.g., EIA, 2002b). Data for some indicators and statistics can be retrieved as far back as 1949 in this interactive and comprehensive report.

These four sources provide data on the production and use of most raw materials (by weight) consumed in the U.S. economy. Other related data sources exist, that link materials data with economic data.

Data on the use of a wide range of commodities in all industrial sectors are published by the Bureau of Economic Analysis of the U.S. Department of Commerce in the form of input-output tables (Bureau of Economic Analysis, 1999). The economic input-output tables include inputs to industry production, commodities consumed by final users, and commodities that are produced by each industry. The tables show transfers of commodities between industry sectors. The amount of a commodity (measured in dollar value) that is required by an industry to produce a dollar of the industry's output and the production that is required, directly and indirectly, from each industry to deliver a dollar of a commodity to final users are also shown. In the tables commodities are broken down into categories sufficient for a "macro" overview of the economy but not for information of a finer resolution. For example, the material content of specific products or trends in substitutions of one metal for another, of plastics for metals, or of materials with less toxicity are not noted. The Bureau of Economic Analysis also holds other valuable national, regional, industry, and international economic-related data (Bureau of Economic Analysis, 2003).

Materials used in products in several industrial sectors, such as automobile manufacturers, consumer durables, and buildings, are published every five years by the U.S. Department of Commerce, Bureau of the Census, in the *Materials Summary* (e.g., U.S. Bureau of the Census, 1997). The *Materials Summary* characterizes physical inputs and outputs between industrial sectors and is organized broadly into product classes. Flows of materials after their use are not tracked well.

An exception has been the Toxics Release Inventory of the U.S. Environmental Protection Agency. Information on the Toxics Release Inventory is publicly available on the Agency's web site (EPA, 2003). More complete data for some industries or for some parts of the country do exist. For example, the State of New Jersey's materials accounting data include not only releases and transfers, but also amounts of chemicals brought on-site, produced, consumed, shipped as product, and kept as inventory (Sidebar 2.1) (Dorfman and Wise, 1997). However, such information is not easily available to the public.

DEFINITIONAL GAPS IN THE DATA

Several areas of importance have significant gaps in the data on material flows, including coverage of materials, spatial resolution (i.e., lack of data at the local level), chemical specificity, and materials related to natural systems. Raw materials are often combined or manufactured into more complex materials or products (e.g., organic and inorganic chemical compounds). There is limited information about the flows of these materials, some of which are valuable and could be subject to increased recycling. Some materials released even in small quantities can have significant environmental impacts, and these materials or their releases also may not show up in a database. Further, with a few exceptions, such as the Toxics Release Inventory and some periodic estimates of the generation of solid wastes, there is little information on the flow of materials into the environment in the form of industrial and municipal solid wastes or as emissions of materials into the air, water, or soil resulting from industrial processes, transportation, and energy generation and use. The information available from the Toxics Release Inventory is not enough to give an accurate picture of these material flows: "In the United States, official government statistics [on waste materials] are insufficient and in most cases served only indirectly as a basis for study estimates" (Matthews et al., 2000). As noted earlier, the Toxics Release Inventory covers only about 650 chemical compounds out of more than 60,000 currently manufactured or used in manufacturing. To monitor and report on the hundreds of thousands of chemicals and the many sources and forms of waste is difficult, expensive, and not the responsibility of any single federal agency. Wastes and emissions are tracked, but a complete picture is not available.

It is important to note that what a government agency considers a waste is more a matter of regulatory definition than a description of a material and its physical properties. Thus, there is an advantage to a complete system of material flows accounts that tracks all materials through their production, use, and release to the environment without regard to current regulatory status. In Toxics Release Inventory reporting, tens of thousands of individual facilities report data tracking material flows that are spatially and chemically well characterized. The flows amount to billions of pounds per year. In contrast, the Environmental Protection Agency's survey of non-hazardous waste survey, which was last done more than a decade ago (e.g., EPA, 1988, 1990, 1992), characterizes flows of waste materials in the industrial and municipal landfill sectors with little chemical detail and little information on the spatial distribution of the flows. Billions of tons of annual material flows were characterized in these surveys.

For many materials, particularly minerals, metals, and wood, pulp, and paper products, data on sources and uses are generally not available in a disaggregated form to allow for material flows accounting at a regional, state, local, or plant level. As mentioned above, materials used in several industrial sectors, such as manufacturing and construction, are published by the U.S. Department of Commerce, Bureau of the Census every five years in the *Materials Summary* (e.g., U.S. Bureau of Census, 1997). There are, however, many gaps in the tables, particularly for quantities rather than value of materials, either because insufficient data were available or because too few companies reported data to enable the information to be published without violating confidentiality agreements. The material category labeled "other" is sometimes one of the largest components in a product, which is not useful.

Although industrial systems and biogeochemical systems clearly interact, the material flows interactions generally are poorly understood. At the global level the grand cycles of carbon, nitrogen, sulfur, and phosphorus are important. These grand cycles are better understood now than in the past; however, future scientific findings will focus on improving this understanding. The most studied of these interactions is the material flow of carbon between systems. The biogeochemical cycling of carbon has been and continues to be extensively studied, but industrial and other anthropogenic releases of carbon to the atmosphere and the generation of the releases by economic development are much less understood.

Other less well known examples of issues related to natural systems are becoming increasingly evident. For example, it is now widely recognized that the nutrient loads on some water bodies are significantly impacted by nitrogen loads from runoff and by atmospheric deposition of air pollutants. Water is another global material for which flows accounts can be compiled, beyond the waste flows currently reported by the U.S. Geological Survey, but this may be a daunting task beyond a single plant or small region (e.g., the watershed level). Ultimately, the details of anthropogenic and biogeochemical flow interactions—particularly their spatial and temporal characteristics—will become increasingly important, and they define a set of research issues, that are discussed more fully in Chapter 7.

In addition to the data gaps in material flows information in coverage, spatial resolution, chemical specificity, and natural systems, differences in definitions and reporting structures for material flows databases are problematic. Many of the databases define flows in very different ways. For example, the Resource Conservation and Recovery Act (42 U.S.C. § 6901 et seq.) biennial survey of hazardous wastes reports total flows of aqueous waste streams, including water, while the Toxics Release Inventory reports releases only of specified chemicals. Since information on composition is not available in the Resource Conservation and Recovery Act database, the two databases are impossible to reconcile. In addition, since the reports are often not submitted in a coordinated manner, information about facilities can be inconsistent. It is not unusual, for example, for the same facility to report different standard industrial classification codes to different databases, making comparisons and coordination among U.S. Geological Survey reports, Bureau of the Census data, and waste and emission flows data extremely difficult.

The contrast between very well characterized material flows accounts performed annually (e.g., by the U.S. Geological Survey) and relatively coarse material flows analyses performed perhaps once every five years or per decade (e.g., by the Bureau of the Census), appears throughout the full range of data sets on material flows. This type of disparity in data collection efforts can be rationalized, but a systemic review of material flows data collection has not been performed. The temporal resolution necessary to support relevant and timely material flows analyses is undetermined.

Developing compatible database structures and analytical frameworks capable of tracking flows that vary in chemical and structural complexity, spatial scale, and magnitude presents significant challenges. Dealing with the complexities of integrating all of the primary data sources also presents challenges. If data collection is distributed rather than centralized, a common database and system is required so that all authorized federal, state, and local agencies and other authorized industry and nongovernmental organizations (see the discussion on partnerships in Chapter 6) can access the data directly. Uniform protocols to enter and delete data will be required to ensure compatibility and accuracy. However, very large computer-based data systems are now available to make data storage and retrieval relatively easy and inexpensive.

SUMMARY AND FINDINGS

There are many sources of data on material flows in the United States, although they are not coordinated or integrated for analysis or public policy-making purposes, nor are they adequate to construct material flows accounts. These sources could be used to begin populating national material flows accounts, but additional data and linkages are necessary for important material flows to be considered appropriately in public policy making. *The committee concludes that there are some good sources of data relevant to material flows, but the data are not yet adequate to populate formal material flows accounts. The committee further concludes that these inadequacies impede the development of sound public policy and business decisions.* **The committee recommends that a national-level effort be initiated to identify and fill significant data gaps that presently impede the development of effective material flows accounts.** Integration and modest supplementation of existing data acquisition programs are thus extremely valuable.

6

The Importance of Partnership in the Conduct of Material Flows Accounting

Material flows accounting could provide useful information for life-cycle assessments, materials optimization and selection, policy decisions regarding sustainable development, and policy decisions regarding resource availability, allocation, and management. A well-conceived and well-executed set of material flows accounts should be multidimensional, requiring inputs from many sources, appropriate data management, and careful quality control of input data and analytical methods. The reliability of the resulting product should be dependent on these circumstances and other considerations throughout the material flows accounting process. Formal material flows accounting can be quite complicated, and an important aspect concerns the precision of the data and the accuracy of account results. Flawed or inadequate material flows accounts may lead to inappropriate decisions and actions. As such, it is crucial that material flows accounting activities be highly participatory and collaborative among parties with appropriate material flows accounting expertise, relevant process knowledge, and familiarity with the appropriate data sets. Such participatory collaborations should be thought of as partnerships in the conduct of materials flows accounting. This chapter explores the characteristics and importance of partnerships in the conduct of material flows accounting, the various roles that contributors would play, and potential impediments to effective partnership of stakeholders.

EXAMPLES OF PARTNERSHIPS

There are many examples of stakeholder partnership in materials-related activities. Most involve the passive transfer of information by organizations to a more active organization developing a work product of use to a broader array of stakeholders. There are fewer true collaborative partnerships with shared active participation. The three examples briefly described below, while all relevant to material flows accounting, represent different lines of inquiry and are illustrative of the wide array of participatory experiences that can occur.

The U.S. Industrial Outlook

The U.S. Department of Commerce prepares the U.S. Industrial Outlook Tables (International Trade Administration, 1995) as an annual economic snapshot of some 600 industry trends in the U.S. economy, broadly compartmentalized into such sectors as nonferrous metals, wood, construction, steel mill products, chemicals and allied products, and paper and allied products. The report catalogues production, consumption, shipments, and trade, from the manufacturing sector to the higher-technology sector, and the service industry sector, for global industry trends, domestic trends, international trade, and growth forecasts. Production of the report involves data identification and acquisition, database development, data analysis, and reporting. Government agencies (e.g., U.S. Geological Survey), industry associations (e.g., the North American Copper Development Association), and individual industries with significant market share provide the data, and the Department of Commerce develops, analyzes, and reports on the database. The report is used by a wide array of government, industry, academic, and nongovernmental public interest organizations.

The Copper Recycling Initiative

The objective of the newly formed industry-government consortium, the Copper Recycling Initiative, is to obtain reliable copper recycling data of global significance. Participating stakeholders include the U.S. Geological Survey, the International Copper Study Group (whose members represent the trade ministries of many countries), and copper industry representatives (e.g., the International Copper Association and the International Wrought Copper Council). These organizations develop and implement strategies for collecting statistics on copper recycling. The group plans to launch its first collaborative data collection activity in 2003. The resulting database will be used by government, industry, academia, and nongovernmental public interest organizations for the development of trends and policies regarding the movement and conservation of copper in the marketplace.

A Life-Cycle Assessment Policy Statement

The Non-Ferrous Consultative Forums on Sustainable Development represents an international initiative with broad multi-stakeholder participation in the development of reports and position papers related to global sustainable development of natural resources. This initiative's reports and papers are intended for use in global policy platforms (e.g., the World Summit on Sustainable Development, held in Johannesburg, September 2002; United Nations, 2003). A policy statement on the use of life-cycle assessment in sustainable development, entitled *Policy Making, Metals, and Life Cycle Studies* (Non-Ferrous Metals Sustainable Development Forum, 2002) has been prepared by this group. The emphasis of the paper is on materials flows guidelines, methodology, and data issues for sustainable development. The group that prepared this paper represents 15 countries involving numerous constituencies, including trade ministries and their representative associations, metals industries and their associations, academic institutions, and nongovernmental organizations.

Life-Cycle Inventory Database

Work is now proceeding on a private-public partnership basis, with funding support from the U.S. Department of Energy, the U.S. General Services Administration, the U.S. Environmental Protection Agency, and the U.S. Department of the Navy. The ultimate objective of the project, known as the U.S. Life-Cycle Inventory Database Project, is to develop publicly available life-cycle inventory databases for commonly used materials, products, and processes. The database is being designed to support public and private sector efforts to develop environmentally oriented decision systems and tools; to provide regional benchmark data for generating or assessing company, plant, or new-technology data; and to provide a firm foundation for subsequent life-cycle assessment tasks such as characterization, normalization, and impact assessments.

The concept of partnership, its value in material flows accounting, and the characteristics of effective partners that have made these examples illustrative of good collaboration are described next.

OBJECTIVES OF PARTNERSHIP IN MATERIAL FLOWS ACCOUNTING

The primary goal of partnership in material flows accounting would be collaborative participation to capture the multidisciplinary and multidimensional aspects of accounts. Important objectives for encouraging collaborative participation in the conduct of material flows accounting include the following:

- To facilitate the completeness of an account
- To overcome proprietary obstacles
- To foster the development of accurate data on industrial processes and product manufacturing
- To strengthen the reliability of the material flows accounting outcome,
- To pool and share resources (technical skills, manpower, co-funding, data)

A deliberate attempt to include partners in material flows account data development and account execution would result in early buy-in, more informed and more robust analyses, participatory decision making, compromise, and understanding of the range of positions, options, variables, and uncertainties.

These objectives are common to all participants in a collaborative material flows accounting scheme. Taken together, these benefits of partnership in material flows accounting would serve to strengthen an account's outcome and utilization.

CHARACTERISTICS OF EFFECTIVE PARTNERSHIPS AND PARTNERS IN MATERIAL FLOWS ACCOUNTING

A well-functioning development process and a reliable database could result from a collaborative partnership with engaged partners. A dysfunctional process has specific undesirable characteristics that promote discord. The features of effective partnerships and partners in material flows accounting are explored in this section.

Effective Partnerships

Partnership can be passive (e.g., occasionally supplying data) or active (e.g., regularly supplying updated data, engaged in the analytical process). Better-quality results are achieved if all partners are active participants in an activity. Partnerships can take the form of collaboration, expert consultation, and advisory review. Collaboration typically involves contribution to the advancement of the work product through coauthorship, sharing of information and data, development of protocols, and/or institutional cofunding and scoping of the direction of the process. Expert consultation involves advancement of the work product through the acquired opinions and analyses of highly knowledgeable individuals. Advisory review involves independent critical evaluation of objectives, scope, and work products in various stages of completion to ensure the robustness of the data from conception to completion. All three forms of partnership will be vital to the success of material flows accounting. A variety of entities should be involved in collecting data that will be useful in their application to material flows activities in the United States (Sidebar 6.1 and Table 6.1).

The success of a partnership is contingent on the motivation of each stakeholder to participate. Motivation, in turn, is driven by each stakeholder's incentive of economics, social responsibility, equity, public welfare, and organizational charter. The most effective partnerships are those based on stable, trusting relationships among partners over time. Such partnerships facilitate the sharing of data particularly between industry and government (i.e., make the process more transparent), and foster ease of communication among partners, understanding of data needs, and timely resolution of issues of conflict, competition, and priority.

Initiatives involving partnership are more participatory if their products are clearly meaningful to each partner's incentives and interests. It follows that initiatives have more successful and sustaining outcomes if the incentives, objectives, and needs of each partner are clearly articulated at the outset, understood by all partners, and regarded throughout execution of the activity. Initiatives involving partnership are more participatory if commitment is top-down (i.e., propelled from the leadership of each partner's organization).

Data in the material flows accounts should be available to the greatest extent feasible, unless proprietary issues demand otherwise. This transparency includes individual intents, data, requirements for confidentiality, potential for conflict, competition, bias, political constraint, trust, and other individual stakeholder concerns. The greater the understanding of these features that exists in the collective engagement, the more effective will be the accounting process and its products.

A few databases involve effective partnerships, most notably those that are government sponsored, are transparent, and make most of their data publicly available. However, a sufficient amount of information is proprietary. Although the information may be proprietary for legitimate reasons, its inclusion impedes the ability to judge the merit of most databases and analysis results in a transparent manner.

Other forms of transparency relate to the substance of a material flows

Sidebar 6.1
Partial List of Stakeholder Partners in Material Flows Activities in the United States

Government Partners

Department of Agriculture (U.S. Forest Service)
Department of Commerce (Bureau of the Census)
Department of Defense
Department of Energy
Department of the Interior (U.S. Geological Survey, Bureau of Land Management)
Department of Transportation
Environmental Protection Agency
National Oceanic and Atmospheric Administration (Fisheries Service)
Office of Management and Budget
State and local governments
Counterpart ministries of foreign governments, as required

Industry Partners

Forestry, metals, aggregate, and petroleum extractive sectors, their downstream fabricators and end-use manufacturers, their trade associations, recyclers, and specific industries

Quasi-governmental International Organizations

North American Free Trade Act Commission for Environmental Cooperation
Organization for Economic Cooperation and Development
United Nations Environment Programme
United Nations Development Programme

Nongovernmental Organizations (NGOs)

Center for the Study of Public Policy
Materials Efficiency Project
Mining Watch
World Resources Institute
World Wildlife Fund

Academic Centers of Excellence

account itself. Hidden flows, data embedded deep within secondary and tertiary production processes, difficult-to-obtain recycling profiles of commodities, realistic pictures of treatment and disposal of waste, and process life-cycle inventories are the elements that will make a material flows account truly meaningful. These elements can be captured only through effective partnerships.

Missing data are becoming an ever-increasing concern as the demand for more complex data grows. From prior experience, we know that many database efforts begin with legislative mandates. Over time, with reduced budgets, lapsed legislative mandates, and staff turnover, commitments to maintaining the integrity of these databases become less of a priority. In addition, databases that are mandated by regulation may become voluntary with time. In some cases, where this has occurred, industry has intervened to maintain the databases. However, such intervention is now waning to the point at which present-day data integrity is impacting the quality of technical analyses. Currently, databases used for commodity material flows analyses are uneven in quality and require careful scrutiny. To compensate for this deficiency, data users must have better relationships with industry to obtain more reliable data and to fill gaps. Initiatives that are voluntary, nonregulatory, and shared by willing partners result in more commitment and buy-in than initiatives that are regulatorily mandated, enforceable, and obligatory.

One of the key objectives of partnership is a coordinated effort to improve the combined database from all contributors. Too often, what is reported in databases is different than what is apparent from surveys of individual industries. This is particularly true for databases that are deliberately disaggregated for material flows analyses of specialized processes or commodity sectors. Without proper coordination among partners, what results is the introduction of hidden uncertainties in the interaction of databases, leading to hidden uncertainties in the outcomes of the analyses.

To ensure the compatibility of data from different sources, highly aggregated databases usually require some form of disaggregation, creating a greater need for reliance on assumptions and more opportunities to introduce errors. Stewards of databases must be technically knowledgeable about the details of their products and the industrial processes on which databases are based, in order to prevent unintentional misuse or misrepresentation.

In general, and understandably, industrial partners have greater familiarity with and knowledge of material flows data that they generate than do the government organizations to which they provide the data. As such, a greater amount of time is spent in follow-up activity among government partners than among industrial partners. It follows that data-

TABLE 6.1 Example of a Metal Flows Account Ledger of Potential Partners

	Data Provider					
	Government					
Activity	DOC	EPA	DOE	DOI	DOD	USDA
Production						
Base Material	X			X	X	X
Manufacturing	X		X	X		X
Service						
Waste Management		X				
Consumption			X		X	X
Recycling	X	X		X	X	X
Import/Export	X		X	X	X	X
Accumulation						
By-products	X	X	X			X
Waste Storage		X	X	X		
Environmental						
As Source		X	X		X	X
As Sink		X	X			X

NOTES: DOC=Department of Commerce and includes Census and Fisheries Service; EPA=Environmental Protection Agency; DOE=Department of Energy;

probing queries within the government require more time to resolve than data probes within industry and are more likely to result in unresolved or unsatisfactory conclusions requiring stop-gap fixes to the database.

Each database and consolidation of databases requires a gatekeeper to ensure quality. Data quality and management are critical. Database managers will be critical participants in material flows accounting activities. It is of concern that current database management and maintenance are uneven. Some databases are well maintained with proper technical management by knowledgeable stewards, while others are not, principally because stewards are not sufficiently familiar with the technical con-

Industry, Association, Commercial					
Producer	Fabricator	Service Providers	Trade and Professional Associations	Commercial Fee-based Databases	NGOs
X			X	X	X
	X		X	X	X
		X			
			X	X	X
X	X		X	X	X
X	X		X	X	X
	X		X	X	X
X	X		X	X	X
X	X		X	X	X
			X	X	X
			X	X	X

DOI=Department of the Interior; and includes U.S. Geological Survey and Bureau of Land Management; DOD=Department of Defense; and USDA=Department of Agriculture and includes U.S. Forest Service.

tent of their databases. Furthermore, database managers are not consistently and effectively engaged as partners. Partnerships deteriorate or end when the quality of information being supplied by any participant is judged to be inferior or to seriously impair the quality of the work product.

It is imperative to identify and include participants as partners and, to the extent practical, representatives from all constituencies whose information is relevant to the mission of the initiative. Omission of any relevant party damages the quality of the product.

Effective Partners

Some teams preparing material flows databases are highly productive, seemingly without much effort. There are some notable features of these partnerships that facilitate this process. Participants are flexible, trusting of one another and of the group, open to alternative ideas, participatory in developing and examining alternatives, contributory to the creative process, constructively critical, in agreement with the objectives of the mission, knowledgeable about processes and data, available for engagement and participation, and willing to share the load. Strong leadership and sound management are of great importance to such highly productive teams.

Sometimes creativity in the collaborative process can be constrained by individual style, personal agendas, and preconceived expectations. Confrontation fueled by rigidity in attitude, sensitivity to disagreement, or to conflict, need to always appear to be right, fixation on particular points of view, and reluctance to be receptive to and accepting of valid alternatives can thwart the process. Sometimes these characteristics are motivated by competition—for funds, market share, information, and so forth. To counteract these tendencies that lead to difficulty, it is important for partners and the leader(s) of the partnership process to foster cooperation, full participatory consideration of alternative points of view, transparency in the deliberative process, and collegiality.

Impediments to Effective Partnerships

It follows that practices contrary to partnership, whether deliberate or resulting from benign neglect, potentially weaken the reliability of outcomes. Almost all practices that ignore or work against partnerships foster exclusion, confidentiality, and loss of transparency. Examples include the following:

- internalizing material flows data within an institutional department without any form of collaborative outreach;
- use of a proprietary methodology (less than full disclosure of how the data analysis was conducted); and
- use of proprietary data (either for individual facilities or as aggregations of facilities within a process sector).

In a competitive marketplace, government regulations, consumer preferences, and downstream manufacturing pressures can drive industrial data or processes to be considered as confidential business information. As such, industries that are the proprietors of the information are often cautious about sharing and participating as partners. Much of this caution stems from liability issues, resource availability, and proprietary concerns. These issues may be magnified on a global scale. Such caution within industry is based on the following concerns:

- There may be the potential for sensitive material flows data to fall into the hands of business competitors.
- A specific material flows analysis outcome might not serve the industry well.
- Individual industry sectors could be perceived as being the cause of a disadvantageous outcome.
- Producers of competitor materials may use material flows data to demonstrate their products' superiority, particularly if the analysis is taken out of context.
- Scholars, activists, analysts, and government regulators could use data to perform their own analyses, reach different conclusions, and promote restricted use of the product or its outright ban.
- Material flows analysis conclusions might lead to application of the precautionary principle to control the material.
- Stronger (i.e., more reliable) material flows data, such as those provided by some upstream raw materials producers and some downstream end-use product manufacturers, could be overshadowed by weaker (i.e., uncertain or highly variable) account data, such as those describing use-phase characteristics and end-of-life recycling.
- A material flows database may be used in further analyses (e.g., life-cycle analysis) in which the common metric on which the analysis is based (e.g., energy gains and losses) for all processes and products may not fairly optimize the benefits of the material.
- Data analysis results could be inappropriately monetized.
- Quantitative scoring systems for ecological and human health risk factors may be inappropriately integrated into material flows databases.

Despite the obvious disadvantages, there may be valid reasons for not promoting transparent partnership, usually related to the sensitivities and impacts of a material flows analysis outcome. Potential impacts from an analysis outcome may compel the practitioner to hold a database in close confidence, at least until it is completed, for reasons that include the following:

- The outcome of the material flows analysis process may, depending on its nature, impact policy, strategy, or future action that is significant to individuals, groups, or society at large.
- The outcome of the material flows analysis process may result in the disclosure of confidential business information to competitors in the marketplace.

The U.S. Geological Survey and the former Bureau of Mines both have a long and respected history of accumulating material flows data in the form of mineral publications and databases. This has been an information-gathering effort for many specific commodity categories, relying on a large amount of voluntary cooperation from the industrial sector. Although a large, established, historical database of selected minerals and metals is available for public use from the USGS, some information has been deemed confidential (i.e., labeled "W" for withheld). Confidentiality of information is a constraint that can limit a contributing partner's involvement in a potential material flows account. Proprietary, or "W", data are usually from a sole-source provider whose condition of participation requires that contributed data be sanctioned. When data can be used in a transparent manner, better commitment of partners and representation of their information results. It is in the best interest of the effort to seek ways of surmounting constraints of confidentiality, such as through data aggregation. Sometimes, the reluctance of individual industries to supply data can be overcome through intervention by industry sector associations working to mediate trust among material flows account stakeholders.

Although some interagency links have been forged, the U.S. Geological Survey's database efforts would be enhanced through even closer partnerships with such other entities as the U.S. Environmental Protection Agency, the National Institute for Occupational Safety and Health, and the U.S. Department of Energy. Further, since metals and minerals represent a global commodity, sharing information on a more international scale would result in more effective application of material flows accounting for policies and practices consistent with sustainability in regional and global contexts. This might include global partnerships with other North American, European, Latin American, or Asian entities charged with the development of their own databases.

Within the United States, barriers among agencies may exist, involving issues of database objective or content and interagency competition for control of the information-gathering role or a preference for no information gathering at all. Nothing would subvert even the most well intentioned and well organized material flows account mission as much as cross-purpose of intent derived from such competition. Competition, particularly among federal departments and agencies, results from jurisdiction of programs, control of programmatic budgets, reluctance to claim ownership of a multiparty work product that influences the operations of one party's organization, and departmental policies on specific issues that impede progress, particularly where the issues relate to legislative mandates or regulatory initiatives emanating from those mandates.

An equally serious impediment would be the attrition of competent staff who are instrumental to the partnership process, inadequate resources to maintain databases, loss of technical understanding about the content of those databases, and divisive use of hidden agendas by one or more participating entities to sway an account initiative. All of these features are counterproductive to accomplishing the initiative's mission. It behooves the partnership team to examine these circumstances and motives early in the process and take decisive remedial action to avoid wasting precious resources.

SUMMARY AND FINDINGS

Participants as partners in material flows accounting activities will be important to the quality of accounting products. The quality will be enhanced when partners are knowledgeable and actively engaged in the process and their legitimate concerns are appreciated and respected. *The committee concludes that partnerships are critical to developing and maintaining material flows accounts.* The most effective partnerships are those based on stable, trusting relationships among partners over time where all gain from the compiled information, and these partnerships will be critical to the success of material flows accounting. **The committee recommends that any process for developing material flows accounts be based on a partnership approach.** Partnerships among all relevant stakeholder groups should be encouraged, with strong leadership, representation appropriate to the material flows accounts under consideration, active participation in the accounting activity, and regard for each participant's motivations and incentives for participating. **The committee recommends that the system be designed to allow for the inclusion of proprietary data, while protecting business confidentiality.** Transparency of the data from all sources, including proprietary data held in industrial and academic databases, should be encouraged.

7

Research Challenges for Material Flows Accounting

Chapter 1 notes that attempts to solve increasingly complex systemic problems are likely to benefit from enhanced versions of material flows accounts. Consequently, the study and use of material flows accounting have a substantial need for research in new methods of material flows accounts and analysis. The research needs fall into two broad categories: first, as the development of the material flows accounting system progresses, research will facilitate successive improvements as the system matures; second, material flows accounts will provide an important foundation and structure for integrating data. These data could be used to support an emerging National Science Foundation (NSF) program focusing on the need for "environmental synthesis to frame integrated interdisciplinary research questions and activities and to merge data, approaches, and ideas across spatial, temporal, and societal scales" (NSF Advisory Committee for Environmental Research and Education, 2003). The most common and simplest material flows analysis is one performed for a single geographical region, for a single material, and at a specific point in time, for example, the amount of steel entering the United States in one year. There are, however, a number of types of material flows accounts that could be developed, each of which has the potential to bring additional insights or to provide additional utility. Few of these extensions of existing standard material flows accounts (primarily in Europe) have been explored extensively by scientists or economists. Nonetheless, it is potentially beneficial to investigate the ways in which they might best be assembled, characterized, and integrated with the more standard types of material flows accounts and the ways in which they might be made most efficacious. This chapter presents examples of some of these potential extensions to standard material flows accounts and analysis methods and briefly discusses their status and prospects. These examples—illustrative, not comprehensive—are largely enhancements of the standard material flows accounting structure and, thus, would be expansions of the proposed material flows accounting framework for the United States. They are windows into the future potential of material flows accounting and analysis.

SPATIALLY DISCRETE MATERIAL FLOWS ACCOUNTS

A spatially discrete material flows account is one that quantifies stocks and/or flows for a specific geographic area and also locates those stocks and/or flows at specific spatial locations within the area. Most current material flows accounts refer to a specific geographical area (usually a country), but not to the spatial locations of the various stocks and flows within that area. Spatial information would help identify opportunities for resource sharing among industrial firms, the development of collection and processing plans for discarded material, and analyses of the potential for environmental impacts resulting from material dissipation.

As an example of a spatially discrete material flows account, Plate II(a) shows the spatial population in China, coded by density, and Plate II(b) shows the light emitted from energy-utilizing activities in China as monitored by satellite. (Light has been shown to be a fairly accurate measure of total energy consumption; Elvidge et al., 1997). Plate II(c) combines the two images. It is immediately apparent that Hong Kong (bottom, right of center) is using energy at a high rate, more or less consistent with its high population density. In west central China, however, a large population is using extremely modest amounts of energy. Spatial information on materials and energy utilization not only reveals the current resource use (fossil fuel energy in this case), but also provides a basis for thinking about trends, possible future scenarios, and policy options for the further development of China's energy infrastructure.

There are a few other examples of spatially discrete material flows account-related studies. In one, energy use in Osaka has been analyzed spatially (Shimoda et al., 2002). In another, the stocks of copper in Cape Town, South Africa, have been estimated (van Beers and Graedel, 2003). A number of geographical information system databases provide platforms upon which materials stocks and flows might be studied. These spatially discrete databases include urban water supply systems, locations of residences and industrial buildings, and population densities; they have seen little use thus far for material flows accounting purposes.

The construction and analysis of spatially discrete material flows accounts must be explored for a number of sample materials and locations. Urban areas are probably the most beneficial places to begin because they are major reservoirs of in-use materials and because supporting geographic information is often available. Two approaches might be taken: (1) "top-down" (i.e., taking higher-level spatial data and distributing it spatially by some protocol), and (2) "bottom-up" (i.e., taking representative spatial data on a locally distributed basis and assembling them by some protocol for the entire region or nation). Research using both approaches is needed.

MATERIAL FLOWS ACCOUNTS OF LINKED SYSTEMS

A substantial complexity in material cycle analyses arises if two or more cycles are closely coupled—that is, if a change in stocks or flows, for example, in the cycle of one chemical species significantly influences the cycle of another. In such cases, accounting approaches that treat the cycles as completely independent will not capture the complexity of the actual situation.

Cycles can be coupled in two different ways: by source and by use. The cycles of carbon dioxide and methane are source coupled, for example, since the combustion of fossil fuels produces both gases. Alternatively, the cycles of carbon and nitrogen are use coupled, since plant growth is related to carbon dioxide as a source of carbon for leaf production and to deposited nitrogen as a fertilizer.

A technological example of a source-coupled system is that of zinc and lead. Geological processes of zinc and lead ore formation have strongly coupled the sources of these two metals. The principal ore mineral containing zinc, sphalerite (ZnS, 67 percent zinc), accounts for 90 percent of zinc production. Sphalerite is usually found in association with galena (PbS), the principal source of lead, as at Mount Isa in Australia, one of the world's largest zinc deposits. Here the ore occurs as finely disseminated bands of galena and sphalerite, often with some pyrite (FeS_2), in the host rock, and typically contains 6.5 percent zinc and 5.7 percent lead. Since zinc and lead commonly occur together, the production of one is closely coupled to that of the other. In addition, cadmium atoms frequently substitute for those of zinc in sphalerite, and the processing of that ore is the leading source of commercial cadmium.

One way in which material cycle coupling occurs in use is when two or more metals are combined into an alloy such as bronze (copper and tin), inconel (copper and nickel), or stainless steel (iron, nickel, and chromium). Additional use coupling occurs in the copper-zinc system when more complex brass-like alloys are made. The brass-lead coupled system is used in castings for plumbing fixtures (which is now being phased out in favor of other, lead-free alloys) and the screw-machine stock used in large quantities to make fasteners.

In the case of natural systems, a modest amount of attention has been given to the coupling of carbon and nitrogen, as mentioned above. For anthropogenic systems, virtually no attention has been paid to identification and analysis other than the recognition that coupled cycles exist.

Few materials have cycles that are substantially independent, yet there is little in the way of analytical approaches to linked cycles. A few studies of such cycles should be undertaken to begin the development of tools for their analysis.

DYNAMIC MATERIAL FLOWS ACCOUNTING

Dynamic material flows accounting examines changes in stocks and flows rather than the stocks and flows themselves. Dynamic material flows accounts look to historical information on materials generation and use to study trends over time. The data requirements are substantially greater than for traditional material flows accounts since time histories must be generated and analyzed.

The flow of stocks of polyvinyl chloride plastic from use to waste management over time is the subject of a demonstration model for a dynamic material flows account conducted by Kleijn et al. (2000). In this work, the rate of generation of discards of polyvinyl chloride plastic was modeled using different assumptions of inflow and lifetime relative to different uses (Figure 7.1). The rate can differ substantially depending on the values of relevant variables, few of which are currently monitored. If such data are routinely available, planning for recycling, energy recovery, and disposal could be undertaken with significantly increased confidence.

Another area in which dynamic flow information would be useful is in evaluating the effects of initiating a large new use of a material or of discontinuing an existing large use. An example of the challenges in this regard is presented by the use of platinum in catalytic converters for automobiles. Regulations in North America and elsewhere, designed to reduce the emissions of smog-forming chemicals, mandated the use of catalytic converters by the mid-1970s (Hegedas and Gumbleton, 1980). Because each converter contains several grams of platinum group metals, a new demand for these metals emerged, doubling their production from virgin ores in less than a decade. It took some 20 years for converters to become ubiquitous in the countries where regulations existed (Grübler, 1998), and the supply system was able to ramp up sufficiently to meet the demand. The situation remains uncertain at this point because increased requirements in greater number of countries coincide with possible major uses of platinum group metals in electronic circuits (Gediga et al., 1998),

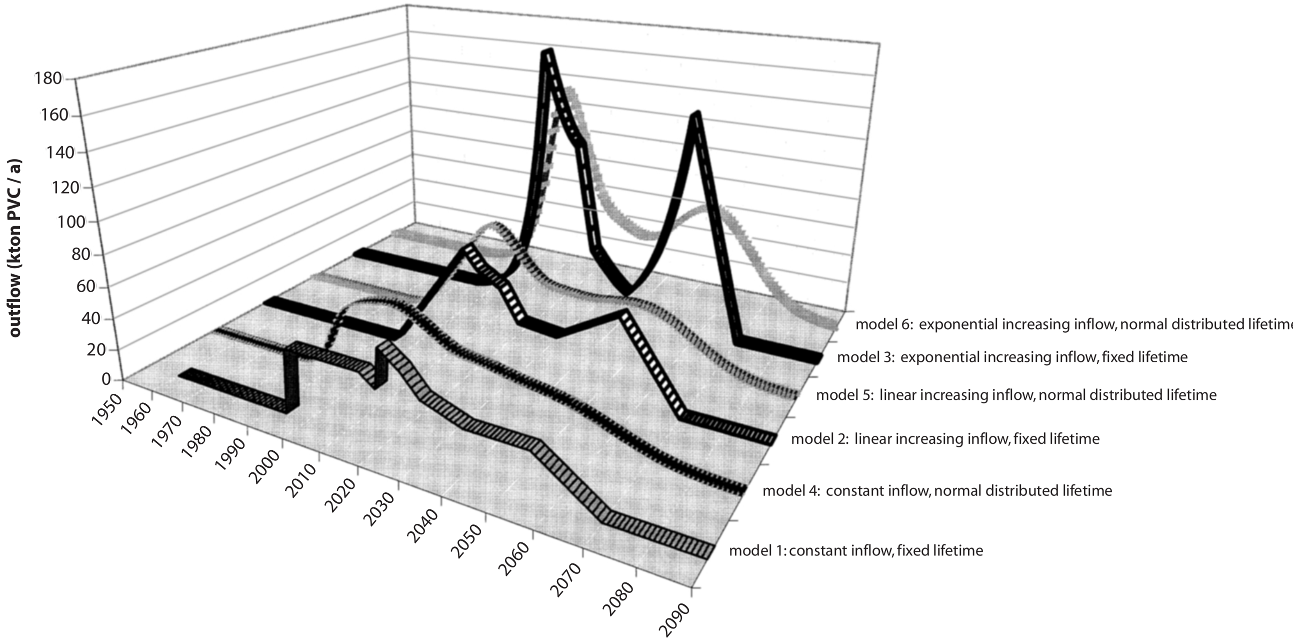


FIGURE 7.1 Development of the generation of polyvinyl chloride waste as a result of the dynamics of the three major polyvinyl chloride applications, assuming different models. SOURCE: Kleijn et al., 2000. Reprinted with permission from Elsevier.

in fuel cells (Appleby, 1999), or in batteries (Dyer, 1999). Should any of these situations occur, platinum supplies for catalytic converters would once again become problematic. Uses of materials demonstrate price elasticity in some cases that is, a rapid increase in the price of a material in use inspires a shift to a cheaper material. Prices are not simply signals of absolute scarcity; they more often reflect shorter-term conditions such as the rate of economic growth, tariffs or other trade barriers, or political or social instability. Thus, where a simple substitution (e.g., plastic for metal) is available, price elasticity drives substitution. Where the application is highly dependent on a specific material (e.g., platinum group metal catalysts), price signals are reflected only weakly and over long time periods as far as substitution is concerned.

Dynamic material flows data are currently available only opportunistically and generally only for the early stages of resource cycles. As noted in earlier chapters, the U.S. Geological Survey, for example, has good dynamic data for mining and processing of metals, but not in general for manufacturing or waste management. It would be advisable to conduct a few investigations of comprehensive dynamic cycles in order to evaluate how challenging it would be to gather such data routinely and how much value might arise from their efforts.

MULTILEVEL MATERIAL FLOWS ACCOUNTS

A multilevel material flows account is one that is carried out in such a way that more than one level (e.g., state, country, and region) is treated as part of a single analysis. Individual material flows analyses have been conducted almost entirely at a single spatial level. This approach strongly resembles the tendencies in biological ecology to restrict one's studies to a single temporal and spatial level, for example this season's vernal pools or half-hectare ecosystems or landscapes, thus avoiding the challenges of studying "how the signatures of actions at one level manifest themselves at levels higher and lower" (Levin et al., 1997, p. 334). In financial accounts, multilevel approaches (at city, state, and federal levels, for example) are not uncommon and have demonstrated much value in understanding and relating otherwise uncorrelated information. In material flows accounts there is also evidence that these multilevel issues are important, perhaps even crucial. Environmental, resource, and technology issues clearly intersect at different levels, as when energy use in rural Alabama contributes to the potential for global climate change or when the rate of extraction of metal ores is dramatically changed by population migration to rapidly evolving cities.

The stocks and flows project at Yale University has recently completed a contemporary copper cycle on several spatial levels (Graedel et al., 2003).

The work treats in detail four stages of resource life: extraction and processing, fabrication, use, and end of life. The data set consists of cities (2 examples), countries (61 examples), regions and continents (9 examples), and the world. Assessments for 14 types of copper use are followed for each country and then aggregated to regional and global scales.

As an example of the results, comparative annual rates of copper entering use in Asian countries around 1994 are shown in Plate III(a). It is of interest to note that the rates are identical for China and Japan at 1,200 gigagrams of copper per year, far higher for those two countries than for any others. South Korea and Taiwan have annual rates that are roughly equivalent at around 400 gigagrams of copper per year, about one-third of those of China and Japan. The rates for Malaysia and Hong Kong are a factor of two lower still. Several countries group around annual use levels of about 20 to 100 gigagrams of copper per year.

Results for the same parameter on a regional basis are shown on the world map in Plate III(b). These rates of use, like those of individual countries, reflect both domestic production and product imports. Asia's rate is the highest, but it is not much greater than those of Europe and North America. The rates for all other regions are less than 10 percent of those of the top three.

This early example of the development of a multilevel material flows account is promising, but clearly represents work in progress. It is advisable to explore multilevel material flows accounts for a number of different materials systems and locations in order to gauge their potential usefulness. The topic remains a potentially rich area for research leading to substantial practical applications.

MATERIAL FLOWS ACCOUNTS OF NATURAL SYSTEMS

Material flows accounts can, in principle, be constructed for any system, whether or not the system contains human agents. For example, one could think of nutrient, carbon, or energy flows accounts for natural ecosystems as examples of material flows accounts of natural systems. This type of accounting has, in fact, been popular and useful in ecosystem ecology (Lindeman, 1942; Hannon, 1973). The fact that material flows accounts can be constructed for any system also makes them good candidates for comprehensive analysis of linked natural and human systems (e.g., Isard et al., 1972). The most common type of natural system material flows account has been the type that traces a single element though the various compartments of the system. For example, nitrogen, carbon, phosphorus, and other elemental "budgets" or accounts have been constructed for a wide range of ecosystems at multiple scales from small microcosms to the entire Earth.

In addition to single-element material flows accounts, multielement (or multicommodity) material flows accounts have also been constructed for natural systems (Costanza et al., 1983) and for linked natural and human systems (e.g., Patterson, 2002). These studies have shown the feasibility and utility of constructing multicommodity material flows accounts that can address the interdependences among commodities.

A major limitation in constructing material flows accounts for natural and linked human-natural systems (as with all material flows accounts) is the difficulty and expense of assembling the data on all the intersector exchanges. In natural systems (unlike human systems) the entities involved cannot report to a central authority on their activities and instruments, and monitoring networks must be constructed to measure material and energy exchanges directly in the field. Given the growing importance of ecological concerns, these kinds of monitoring networks are nevertheless becoming more widespread. The NSF-funded long-term ecological research network of research sites is one example, as is the proposed national ecological observatory network. The data collected via these ongoing sites could be integrated into ongoing material flows accounting efforts for natural and human-natural systems to yield significant new insights.

Coupling material and energy flows data, including emissions to air, land, and water, with biological and physical information could help focus public policy making on the following key issues, which concern people and governments: (1) climate change, (2) the environment, (3) biodiversity (flora and fauna), (4) public health, and (5) quality of life (and the economy). Focusing on these key issues, the following bullets paraphrase the action items of the Sixth Community Environment Action Programme (European Parliament and Council of the European Union, 2002):

- Climate change has emerged as an important outstanding challenge hinging on anthropogenic impact, primarily because of energy production and consumption. National and worldwide initiatives have evolved to curb global warming, but good data and indicators derived from analyses of data will ultimately guide the initiatives and be used to formulate global agreements on climate change.
- On a national and global scale, public policy initiatives on the protection, conservation, restoration, and—sometimes—development of the functioning of natural systems, natural habitats, and wild flora and fauna have to be informed with good data and derived indicators, and they will be pursued with the aim of halting desertification and the loss of biodiversity, including the diversity of genetic resources.

• Ultimately, better resource efficiency and resource and waste management systems will be founded on more sustainable production levels and consumption patterns, thereby decoupling the use of resources and the generation of waste from the rate of economic growth and aiming to ensure that the consumption of renewable and nonrenewable resources does not exceed the carrying capacity of the environment.

The H. J. Heinz III Center for Science, Economics, and the Environment report on *The State of The Nation's Ecosystems* (H. J. Heinz III Center for Science, Economics and the Environment, 2002) provides "a blueprint for periodic reporting on the condition and use of ecosystems in the United States," aimed at informing public policy making with scientifically sound and unbiased data and analyses. It structures reporting of indicators across six different ecosystems, defined on the basis of land cover (i.e., coasts and oceans, farmlands, forests, fresh waters, grasslands and shrublands, and urban and suburban areas). Indicators focus on system dimensions (extent, fragmentation, and landscape pattern), chemical and physical conditions (nutrients, chemical contaminants, and physical conditions), biological components (plants and animals, biological communities, and ecological productivity), and human use (food, fiber, and water as well as other services, including recreation). While identifying data gaps (data are adequate to support national reporting for 58 of 103 indicators, and data are considered complete for only 33 of the 58 indicators), the report defined "what should be measured, counted and reported so that decision makers and the public can understand the changes that are occurring in the American landscape." A material flows accounting system would be a significant source of data for the full development of indicators across ecosystems.

SUMMARY AND FINDINGS

Clearly the research agenda for material flows accounting and material flows analysis is rich and exciting, and further development would likely enhance the traditional materials accounting structure and its related analytical outputs in useful ways. Indeed, with financial accounting as a model, it appears virtually impossible to contemplate a materials accounting program that does not include such activities.

The focus of this chapter has been on research challenges in material flows accounting. As with all research, the most useful outcomes cannot be predicted. It is apparent, however, that the research will benefit from accounting systems that provide information on cycle linkages (e.g., reporting copper and copper alloys in separate categories rather than as one merged category). Similarly, the development of multilevel material flows accounts (e.g., individual states, the United States as a whole, North America as a whole) will provide the basic information from which research can generate new analytical approaches and new conclusions. Material flows accounts are good candidates for comprehensive analysis of linked natural and human systems. Monitoring networks would need to be constructed to measure directly material and energy exchanges in the field.

The committee concludes that a comprehensive material flows accounting program requires a research component that explores tools and analytical approaches to studying stocks and flows that vary over space and time, that treats multiple organizational levels, and that explores the complexities and benefits of cycles linked by nature, by technology, or by a combination of the two. **The committee recommends that relevant government agencies support research related to material flows accounting.**

8

Implementation Strategy

Although falling short of creating formal national material flows accounts, the United States possesses numerous databases, accounting based and statistical in nature, which could support the development of such accounts for the purposes described in this report. Specific studies using material flows accounts have been cited in earlier chapters, and from these efforts, significant insights on an effective strategy for implementing material flows accounts can be gleaned. The material flows data already being developed at various levels (from the local to the national to the international) clearly demonstrate the value of material flows accounting, but the data are not being used as effectively as they could be if there were a consistent framework and system to link data at various levels. Further, the extent of accounts development and the nature of materials to be included are yet undetermined for any formal U.S. application.

The committee notes that a formidable amount of work will be required in designing a robust system of material flows accounts, to whatever extent eventually justified—a notion reinforced by the European Union (Eurostat, 2001). Regardless of scale, intensive work will be involved in pulling distributed material flows databases together into a common system of prioritized accounts of quality data that will lead to accuracy in derived indicators and analyses. Further, the trade-offs regarding the extent of accounting system development, the nature and level of details of materials to be tracked, the cost of development, and the perceived benefits that will be derived from their use will have to be reconciled through extensive interactions among divergent constituencies.

A successful implementation strategy for material flows accounting will be the key to its effective use in public policy making. An important element of the strategy would be the nature of the organization and its functionality. The committee discussed options for creating the organization, which are presented below. However, regardless of the organizational structure established to effect material flows accounting in the United States, certain characteristics will be necessary.

MISSION AND GOALS OF THE ORGANIZATION

Clearly stating the mission and specifying the anticipated goals of the material flows accounting organization will be a necessary first step. The mission should focus on the key purposes for establishing material flows accounts and the desired outcomes from using them. An example, based in part on the European Union mission (Eurostat, 2001) statement follows:

> The mission of the Material Flows Accounting Office [organization] is to develop and maintain a common database system that will provide material flows information, which can be integrated into analyses of physical and economic systems, thereby permitting more robust public policy decision-making.

Related to the mission, organizational goals would focus on what specifically is anticipated from establishing and using the system of material flows accounts. Examples—not comprehensive—goals follow:

- For a specified system with definable boundaries (e.g., the U.S. economy) and a specified period, accurate material flows accounting will provide (1) an aggregate view, in physical units (e.g., tons), of the intensity of inputs to the system and outputs from the system to the environment; (2) the changes in stocks of materials in the system; and (3) the flows of inputs to and exports from the system.
- For a specified system, material flows accounting, along with procedures for estimating uncertain flows as accurately as feasible, will permit the calculation of an accurate mass balance.
- Material flows accounting and mass balances for targeted materials, at times coupled with other databases, will allow the derivation of indicators of impacts on the economy, people, and the environment.
- Material flows accounting and various analyses will allow the tracking of targeted materials (e.g., toxic or hazardous substances) and the determination of secure or safe ways to handle or store them.
- Material flows accounting can provide valuable data for use in life cycle assessment, which in turn may be used to design products or manu-

facturing or utilization processes to reduce adverse impacts on people and the environment or improve economic benefit.

- Focusing on improving energy efficiency, accounts and analyses may be used to improve the recycling and reuse of materials, thereby advancing manufacturing sustainability.
- Material flows accounting and analyses may provide information to remove or mitigate regulatory and jurisdictional impediments to recycling and other beneficial reapplication or reuse of materials.
- Accounting and analyses can be used to inform the substitution of materials for national security purposes.

PARTNERSHIP—A KEY TO SUCCESS

As noted in Chapter 6, a deliberate attempt to include partners in material flows accounts data development and material flows analysis applications could result in early buy-in, better (more informed or robust) analyses, participatory decision making, rational compromise, and understanding of the range of positions, options, variabilities, and uncertainties. Conversely, data development and material flows accounts applications in isolation could result in narrowly focused analyses, data gaps, skewed (biased) outcomes, reduced expectations, reduced implementation of material flows accounting conclusions, adversity, suspicion, fear, and resistance.

The committee believes that a broad range of proactive partnerships is necessary to ensure successful development, implementation, and effective use of material flows accounts. However, significant impediments to building effective partnerships will have to be overcome, as discussed in detail in Chapter 6. The ongoing work of the U.S. Geological Survey and the Bureau of Economic Analysis provide robust partnership-based models for data collection and analysis.

IDENTIFYING AND SELECTING AN ADVISORY COMMITTEE

A multidisciplinary advisory committee of expert partners should initially specify data needs for targeted materials reflective of cost-benefit trade-offs, including integration, structuring accounts to address these needs, and developing a protocol for creation, prioritization, and population of accounts. After the initial work has been accomplished, the advisory committee would then guide successive steps aimed at achieving maturity of the system; coordinate the data input to the system by various stakeholders; and coordinate the research agenda to improve the system of accounts and linkages to other databases.

COLLABORATIVE PROTOCOL NECESSARY

Successful use of material flows accounts for sound public policy making hinges on cooperation among government, business, and the public. Regardless of the form of the organization, an important task is to establish the databases through the efforts of various stakeholders based on criteria and a protocol to ensure that those criteria are satisfied. Elements of such a protocol include data quality, transparency, and formatting to ensure access.

PRIORITIZING MATERIAL FLOWS ACCOUNTS

Not all materials in a specified system have to be tracked for sound public policy making; rather, reflective of practical and economic considerations, successful implementation would require that selected material flows accounts be structured and populated according to a protocol. This does not necessarily require an expansive new data collection program, but targeted material flows data from existing distributed database systems may be pulled into a common accounting system that reflects the benefits related to costs. Areas of potential highest benefit will have to be determined while considering the optimal spatial levels of implementation, the scope of targeted materials, and the associated scale of accounts development. Determining the order of accounts development requires a prioritization system, which should be part of the protocol. Many criteria could be used to determine priority materials for which accounts would be established. An incomplete list includes the following: economic importance, scarcity, volume, goal-based impact, ease of collection, and risk.

GLOBALIZATION OF ACCOUNTS

Just as materials flow across national boundaries from import and export activities, so must the data to ensure full and accurate accounting of targeted materials. The Eurostat (2001) report also acknowledges this eventuality, which could well become part of doing international business beyond the European Union, much as International Standards Office (ISO) guidelines have been incorporated to ensure quality control (ISO 9000) and improve environmental management systems related to business (ISO 14000). For these reasons, the committee encourages the U.S. material flows organization to explore the usefulness of integrating international data into the nation's databases. The committee also encourages the design of the U.S. system so that it is compatible with a global (e.g., the European Union and Japan) materials accounting and flow analysis system in terms of definitions, standards, and measurements.

OUTLINING AN INITIAL RESEARCH AGENDA

Even though there are substantial existing data for the early development of formal material flows accounts, additional important issues will arise concerning the scope of these accounts and of the data in them, as well as their uses, such as estimation methods for indirect or hidden flows and their impacts, estimation of the level of recycling and its contribution to resource conservation, procedures for balancing inputs and outputs, and derivation of the most appropriate indicators of various measures of performance. Chapter 7 outlines many other research issues in detail.

Working together, government agencies, the industrial sectors, researchers, and other users of the data will undoubtedly have to capture the issues that arise, which will require further research for solution or better understanding. For example, many gaps in data collection are certain to be found, and a key task will be to examine the trade-off between additional data collection and the use of proxy data. Further, there will be opportunities to improve the material flows accounting framework and the accounts themselves over time, thereby moving the entire process to a higher functional level. Anticipating the inevitably of such issues, a material flows accounting organization must coordinate collaborative development among government agencies, industrial sectors, researchers, and other users to form a long-range vision. The vision would focus on emerging issue-oriented studies for supplementing the material flows databases, thereby filling the important gaps; completing the accounts; and developing standards for the reliability and quality of data as well as appropriate qualitative descriptions and quantitative limits for the data.

SUPPORTING ONGOING ACTIVITIES

As mentioned above and in Chapter 5, a number of separate databases are available in the United States from which substantial material flows data can be obtained. These data have already proved useful, as described in Chapter 4—in some cases in a way relevant to public policy making. They also provide an historical repository from which dynamic analyses of material flows and their impacts may be done. Significant government expertise already exists in the agencies that collect, maintain, and report on these data. Thus, the creation of material flows accounts requires that these data be available for incorporation into a formally structured common database system. The committee believes that it would be cost-effective to maintain the current material flows data and expertise, at least initially. As prioritized accounts are established and become functional, the activities of existing government data sources should be evaluated. *The committee concludes that the present level of data collection and analysis* *must be maintained as an essential foundation for the initial development of structured material flows accounts.* **The committee recommends that the present material flows data activities of the federal government, including those of the U.S. Geological Survey, U.S. Environmental Protection Agency, and Departments of Commerce and Agriculture, be maintained at least at their current levels of activity.** Budgetary support must be sufficient to allow the activities to continue at levels that will maintain the integrity of the present databases**.** Sufficient resources must be available to replace retiring personnel and maintain staffing levels. If a decision were made to establish a system of national material flows accounts, staffing levels would likely have to be enhanced to support the effort.

ORGANIZATIONAL OPTIONS AND RECOMMENDATION

The scope of work discussed above generally includes work to convert data from existing distributed databases to the formally defined, modular material flows accounts structure. The cost of this effort goes beyond the cost of maintaining the distributed databases (by the home agencies) and requires that a working staff be established to populate, maintain, and use the accounts. The size of this staff depends on the extent to which materials are targeted by the partnership for inclusion, as well as the frequency of reports, analyses, and extended uses (e.g., derivation of various indicators), expected to be annual after the system is functional. An advisory committee should assist the administration of the organization in defining, organizing, and prioritizing accounts.

A number of options may be pursued in establishing and funding the material flows accounting organization, but it should be founded on a partnership-based consortium of industry, government, academia, and other committed stakeholders. The primary functions of the organization must include defining, organizing, prioritizing, populating, implementing, using, reporting on, and allowing access to selected accounts and associated target materials. The establishing action would have to ensure the active participation of representatives from organizations and agencies that perform material flows-related functions. Potential options for creating and funding the organization include the following:

Implementation in a Government Agency

Although numerous material flows-related databases exist across agencies, the creation of the formal system of material flows accounts in a lead agency is viable, provided it is given authority and a budget commensurate with the responsibility relative to a formal charge and mission.

The establishing action must define where the organization will reside within an agency (e.g., exactly where in the Department of Commerce) and the working relationships among the lead agency and the many other material flows data providers in other agencies and externally. The establishing action must also mandate a multiple-constituency advisory committee, comprised of a core team of experts, to ensure that an effective partnership is used in resolving complex issues as work is pursued. This scenario would be relatively easy to mandate, perhaps the most cost-effective scenario, but the committee perceives that it would present a challenge to establishing an effective partnership. Specifically, this type of organization may not be able to embrace a full range of issues in the broad context, presented in Chapter 3. It would provide direct federal oversight, as in most countries, that have implemented material flows accounting systems.

Government Task Force

Although the use of a task force historically relates to the accomplishment of temporary or formative tasks, it is possible that an interagency- and multiple constituency-based task force, or working group, could be established on a more extensive basis, similar to those for homeland security and energy policy. This is envisioned as a high-level, executive branch-based task force over an initial period (e.g., 5 or 10 years) with transition to one of several other forms of permanent organization later, after the system has been designed completely, implemented to the extent justified, used to generate relevant indicators and reports, and determined to be successful for permanent implementation. An advisory committee could either be a part of the working group or a stand-alone advisory committee to a working group of representatives from appropriate government agencies (e.g., The Departments of Commerce [Bureau of Economic Analysis], Interior [USGS], Energy [Energy Information Administration], Environmental Protection Agency, White House Office of Science and Technology Policy). This scenario would present high visibility, at least initially, for a material flows accounting mission and provide impetus for start-up and early implementation. The transition from a temporary to a permanent organization is problematic. The public perception that a task force is often ineffective must be overcome. The effectiveness of a task force charged with the actual work could be compromised if members retained significant duties and responsibilities with their home organizations. There could also be a potential for conflict of missions.

Independent Organization Affiliated with a Government Agency

As an alternative to housing such an organization and its authority within a single lead agency with an advisory committee, it might be established as a completely independent organization, similar to the Energy Information Administration, associated with a coordinating or enabling agency, similar to the Department of Energy. Authority and a budget would be vested in a head, or administrator, of the organization, who would interact with the coordinating agency and the advisory committee. This approach would give more decision-making authority relative to material flows accounting to the independent organization, which must be responsive to the multiple-constituency advisory committee, thereby better ensuring an effective partnership effort. For cost savings the coordinating agency would coordinate organizational activities and facilitate the organization's functionality; however, formal decision making and its outcomes, as they impact other agencies, would be done by the organization itself. In this scenario the establishing action must ensure that representatives of the agencies that currently perform material flows related activities participate actively in processes.

A New Center

The final organizational strategy considered by the committee was the establishment of an independent center, similar to those established by the National Science Foundation. A center focusing on the creation, implementation, and use of a material flows accounting system could be established through a competitive solicitation (e.g., through the National Science Foundation). The mission and charge of the center and its function would be specified in detail in the solicitation, which could be formulated by an interagency working group on material flows accounting. The center would consist of an administrative unit and of units that focus on various aspects of defining, organizing, prioritizing, populating, implementing, using, and reporting on selected accounts and associated target materials as well as researching related issues. To ensure its effectiveness, the center could be re-competed on a periodic basis, say every five or ten years. The center would also be responsive to an advisory committee comprised of experts from multiple constituencies. The establishing action would have to ensure the active participation of representatives from agencies that perform material flows-related functions, a participation that transcends the role of advisory committee membership. Gaining the level of activity from government experts as well as the relevant data would be problematic. An organization that is independent of the government would not have the same level of national support, visibility, or impact as would an organization under direct government authority. The budget needed to achieve full functionality would likely be more than for other scenarios, and in certain cases the costs for some activities would be duplicative.

Recommendation

Having examined several options, the committee concludes that an independent organization is the most likely option to ensure success of material flows accounting in the United States. The committee believes that it will help the partnership process if the organization is separate from existing data providers. **Accordingly, the committee recommends that an independent organization, comprised of interdisciplinary experts, be created and funded through a formal process.**

The committee converged on the independent organization option as the most likely to ensure success of material flows accounting in the United States in the pursuit of sound, holistic public policy making. However it is created, authorized, and funded, such an organization—although necessarily independent—must be given a specific mission and charge related to the provisions in this chapter, including the tasks outlined above. To ensure its effectiveness, detailed interactions must be established with U.S. agencies that currently perform material flows data collection and analysis.

The material flows accounting organization must be comprised of a broad core team of interdisciplinary experts, augmenting the advisory committee and government partners. Specifically, the broader core team will have to consist of experts with knowledge of and experience in the fields of environmental science; design engineering; industrial ecology; geology and/or geological engineering; agricultural, energy, forestry, and mineral industries; economics; biology and chemistry; epidemiology, toxicology, and/or occupational medicine; survey development and data collection; database systems and management; and possibly others.

SUMMARY

As concluded in Chapter 5, the establishment of material flows accounts and their use in material flows analyses will improve public policy making. Ultimately, the accounts and analyses using them can be coupled with economic, quality of life, and environmental information to give integrated-impact input on public policy. Much of the progress in this arena will be enhanced by ongoing research, which will run concurrently with the development of material flows accounts.

The strategy for successful implementation of material flows accounts is important to ensure success in using them. By employing a partnership approach through an independent organization, the accounts and their uses would be enhanced, and through this enhancement, linkages with other databases on the economy, the environment, and social status could lead to the type of holistic public policy making necessary for a progressively more complex society.

References

Adriaanse, A., S. Bringezu, A. Hammond, Y. Moriguchi, E. Rodenburg, D. Rogich, and H. Schütz. 1997. Resource Flows: The Material Basis of Industrial Economies. Washington, D.C.: World Resources Institute, 66 pp.

Allenby, B., J. Ciccarelli, I. Artaki, J.R. Fisher, D. Schoenthaler, T.A. Carroll, A.M. Lyons, D.W. Dahringer, Y. Degani, T.E. Graedel, J.T. Plewes, R.S. Freund, C. Gherman, H. Solomon, C. Melton, G. C. Munie, and N. Socolowski. 1992. An Assessment of the Use of Lead in Electronic Assembly. Northbrook, Ill.: IPC-Association Connecting Electronics Industries, 37 pp.

Appleby, A.J. 1999. The electrochemical engine for vehicles. Scientific American 281(1): 74-79.

Brown, III, W.M., G.R. Matos, and D.E. Sullivan, eds. 2000. Materials and Energy Flows in the Earth Science Century: A Summary of a Workshop held by the USGS in November 1998. USGS Circular 1194. Denver, Colo.: U.S. Geological Survey, 71 pp.

Bureau of Economic Analysis. 1999. Interactive Access to Input-Output Accounts Data. Washington, D.C: Department of Commerce. Available at: <http://www.bea.doc.gov/bea/industry/iotables/prod/ table_list.cfm?anon=206#Tables>.

Bureau of Economic Analysis. 2003. BEA's Economic Accounts. Washington, D.C.: Department of Commerce. Available at: <http://www.bea.doc.gov>.

Costanza, R., C. Neill, S.G. Leibowitz, J.R. Fruci, L.M. Bahr, Jr., and J.W. Day, Jr. 1983. Ecological Models of the Mississippi Deltaic Plain Region: Data Collection and Presentation. Washington, D.C.: U.S. Fish and Wildlife Service, 340 pp.

de Cerreno, A.L.C., M. Pancero, and S. Boehme. 2002. Pollution Prevention and Management Strategies for Mercury in the New York/New Jersey Harbor. New York: New York Academy of Sciences, 47 pp.

Dorfman, M.H., and M. Wise. 1997. Tracking Toxic Chemicals: The Value of Materials Accounting Data. New York: INFORM, Inc., 80 pp.

Dyer, C.K. 1999. Replacing the battery in portable electronics. Scientific American 281(1): 88-93.

EIA (Energy Information Agency). 2002a. Monthly Energy Review: December 2002. Washington, D.C.: U.S. Department of Energy, 46 pp.

EIA. 2002b. Annual Energy Review 2001. Washington, D.C: U.S. Department of Energy, 429 pp. Available at: <http://tonto.eia.doe.gov/aer/index2000.htm>.

Elvidge, C.D., K.E. Baught, E.A. Kihn, H.W. Kroehl, E.R. Davis, and C. Davis. 1997. Relation between satellite observed visible-near infrared emissions, population, economic activity, and electric power consumption. International Journal of Remote Sensing, 18(6):1373-1379.

EPA (Environmental Protection Agency). 1988. National Survey of Solid Waste (Municipal) Landfill Facilities. Washington, D.C.: EPA, 74 pp.

EPA. 1990. Characterization of Municipal Wastes in the United States: 1990 Update. EPA-530-SW-90-042. Washington, D.C.: EPA, 130 pp.

EPA. 1992. Characterization of Municipal Wastes in the United States: 1992 Update. EPA-530-R-92-019. Washington, D.C.: EPA, 135 pp.

EPA. 2003. EPA Toxic Release Inventory Program. Available at: <http://www.epa.gov/tri/>.

European Parliament and the Council of the European Union. 2002. Sixth Community Environment Action Programme. Decision No. 16/2002/EC. July 22. Available at: <http://europa.eu.int/comm/environment/newprg/>.

Eurostat. 2001. Economy-Wide Material Flow Accounts and Derived Indicators: A Methodological Guide. Luxembourg: Office for Official Publications of the European Communities, 92 pp.

Fitch, ICBA, Duff & Phelps, LLC. 2001. GASB 34: A New Look and New Tools for Municipal Credit Analysis. New York: Fitch IBCA, 6 pp.

Gediga, J., H. Beddies, H. Florin, M. Schuckert, K. Saur, and R. Hoffmann. 1998. Life-cycle engineering of a three-way catalyst system as an approach for government consultation. Pp. 477-481 in 1998 Proceedings of the Total Life Cycle Conference, Graz, Austria, December 1998. Warrendale, Pa.: Society of Automotive Engineers.

Graedel, T.E., and B.R. Allenby. 1995. Industrial Ecology. Englewood Cliffs, N.J.: Prentice Hall, 416 pp.

Graedel, T.E., D. van Beers, M. Bertram, K. Fuse, R.B. Gordon, A. Gritsinin, A. Kapur, R. Klee, R. Lifset, L. Memon, H. Rechberger, S. Spatari, and D. Vexler. 2003. The multiscale cycle of anthropogenic copper. Environmental Science & Technology, submitted.

Grübler, A. 1998. Technology and Global Change. Cambridge, UK: Cambridge University Press, 462 pp.

Hannon, B. 1973. The structure of ecosystems. Journal of Theoretical Biology 41: 535-46.

Hegedas, L.L., and J.J. Gumbleton. 1980. Catalysts, computers, and cars: A growing symbiosis. Chemtech 10: 630-642.

H. J. Heinz III Center for Science, Economics and the Environment. 2002. The State of the Nation's Ecosystems: Measuring the Lands, Waters, and Living Resources of the United States. New York: Cambridge University Press, 220 pp.

Howard, J.K. 1997. The U.S. Timber Production, Trade, Consumption, and Price Statistics 1965-1997. USDA Forest Service General Technical Report FPL-GTR-116. Washington, D.C.: U.S. Forest Service, 76 pp. Available at: <http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr116/fplgtr116.htm>.

Institute of Scrap Recycling Industries. 2001. Mercury rising. Scrap (Sept/Oct): 32-42.

International Trade Administration. 1995. U.S. Industrial Outlook. Available at: <http://www.ita.doc.gov/td/industry/otea/usio/usio95.html>.

Isard, W., C.L. Choguill, J. Kissin, R.H. Seyfarth, and R. Tatlock. 1972. Ecologic-Economic Analysis for Regional Development. New York: The Free Press, 170 pp.

ISO (International Organization for Standardization). 1997. ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework. Geneva, Switzerland: ISO, 12 pp.

Japanese Environmental Agency. 1992. Quality of the Environment in Japan 1992. Tokyo: Japanese Environmental Agency, 85 pp.

Kimbrough, D., P. Wong, J. Biscoe, and J. Kim. 1996. A critical review of photographic and radiographic silver recycling. Journal of Solid Waste Technology and Management 23(4): 197-207.

Kleijn, R., R. Huele, and E. van der Voet. 2000. Dynamic substance flow analysis: The delaying mechanism of stocks, with the case of PVC in Sweden. Ecological Economics 32: 241-254.

Lebow, S. 1993. Leaching of Wood Preservative Components and Their Mobility in the Environment: Summary of Pertinent Literature. General technical report FPL-GTR-93. Washington, D.C.: U.S. Department of Agriculture, 36 pp.

Levin, S.A., B. Grenfell, A. Hastings, and A.S. Perelson. 1997. Mathematical and computational challenges in population biology and ecosystems science. Science 275(5298): 334-343.

Lindeman, R.L. 1942. The trophic-dynamic aspect of ecology. Ecology 23(4): 399-418.

Llewellyn, T.O. 1992. Cadmium Materials Balance. Washington, D.C.: Bureau of Mines, 20 pp.

Matos, G., and L. Wagner. 1998. Consumption of materials in the United States, 1900-1995. Annual Review of Energy and the Environment 23(1): 107-122.

Matthews, E., C. Amann, S. Bringezu, M. Fischer-Kowalski, W. Hüttler, R. Kleijn, Y. Moriguchi, C. Ottke, E. Rodenburg, D. Rogich, H. Schandl, H. Schütz, E. van der Voet, and H. Weisz. 2000. The Weight of Nations: Material Outflows from Industrial Economies. Washington, D.C.: World Resources Institute, 126 pp.

Mlynarski, K.W. 2000. Survey methods for nonfuel minerals. Pp. 2.1-2.4 in USGS Mineral Yearbook. Reston, Va.: U.S. Geological Survey.

Moriguchi, Y. 2002. Material flow analysis and industrial ecology studies in Japan. Pp. 301-310 in R. Ayres and L. Ayres, eds., A Handbook of Industrial Ecology. Northhampton, Mass.: Edward Elgar.

Moriguchi, Y., ed. 2003. Material Flow Data Book: World Resource Flows around Japan, Second Edition. CGER-D033-2003. Toyko: National Institute for Environmental Studies, 41 pp. Available at: <http://www-cger.nies.go.jp/publication/D033/D033-2.pdf>.

Non-Ferrous Metals Sustainable Development Forum. 2002. Report on Policy Making, Non-Ferrous Metals and Life Cycle Studies. Science, Research and Development Working Group, Subgroup on Life Cycle Assessment. Available at: <http://www.nfmsd.org/wg_research/docs/LCA.pdf>.

NSF (National Science Foundation) Advisory Committee for Environmental Research and Education. 2003. Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century. Arlington, Va.: NSF, 80 pp.

Norris, G.A. 1998. Direct and Upstream Emissions of Carbon Dioxide from Fossil Fuel Combustion: An Input/Output-based Assessment and Comparison of Sectors in the U.S. Economy. Research Project 159614 for National Renewable Energy Laboratory, Golden, Colo.

Patterson, M.G. 2002. Ecological production based pricing of biosphere processes. Ecological Economics 41(2002): 457-478.

President's Materials Policy Commission (Paley Commission). 1952. Resources for Freedom, 5 volumes. Washington, D.C.: U.S. Government Printing Office, 819 pp.

Reid, R. 1999. High tech, low grade recycling. Scrap 56(3): 76-80.

Rejeski, D. 1998. Mars, materials, and three morality plays: Materials flows and environmental policy. Journal of Industrial Ecology 1(4): 13-18.

Shimoda, Y., Y. Takahara, and M. Mizuno. 2002. Estimation and impact assessment of energy flow in urban area. Pp. 727-730 in Proceedings of the 5th International Conference on EcoBalance, Tsukuba, Japan, November 6-8, 2002. Tokyo: Society of Non-Traditional Ecology.

Spencer, V.E. 1978. Raw materials in the United States Economy 1900-1977. Technical Paper 47. Washington, D.C.: U.S. Bureau of Mines, 98 pp.

Steurer, A. 1992. Stoffstrombilanz Österreich 1988 (Substance Flow Balance for Austria). Schriftenreihe Soziale Ökologie Band 26. Vienna: Universitäten Wien, Instituts für interdisziplinäre Forschung und Fortbildung.

Stilwell, D.E., and K.D. Gorny. 1997. Contamination of soil with copper, chromium, and arsenic under decks built from pressure treated wood. Bulletin of Environmental Contamination and Toxicology 58(1): 22-29.

United Nations. 2003. Official UN Website for the Johannesburg Summit 2002. Available at: <http://www.johannesburgsummit.org>.

USDA (U.S. Department of Agriculture). 2003. Agricultural Statistics. Available at: <http://www.usda.gov/nass/pubs/agstats.htm>.

U.S. Bureau of the Census. 1997. Materials Summary 1997. Washington, D.C.: U.S. Department of Commerce, 153 pp.

USBM (U.S. Bureau of Mines). 1989. The New Materials Society, Volume I: New Materials Market and Issues. Washington, D.C.: U.S. Government Printing Office, 141 pp.

USBM. 1990. The New Materials Society, Volume II: New Materials Science and Technology. Washington, D.C.: U.S. Government Printing Office, 274 pp.

USBM. 1991. The New Materials Society, Volume III: Material Shifts in the New Society. Washington, D.C.: U.S. Government Printing Office, 147 pp.

USGBC (United States Green Building Council). 2003. Homepage. Available at: <http://www.usgbc.org/>.

USGS (U.S. Geological Survey). 2001. Obsolete Computers, "Gold Mine," or High-Tech Trash? Resource Recovery from Recycling. Fact Sheet 060-01. Reston, Va.: USGS, 4 pp.

USGS. 2002a. Mineral Commodity Summaries 2001. Reston, Va.: USGS, 197 pp. Available at: <http://minerals.usgs.gov/minerals/pubs/mcs/2002/mcs2002.pdf>.

USGS. 2002b. Minerals Yearbook. Available at: <http://minerals.usgs.gov/minerals/ pubs/myb.html>.

USGS. 2003a. Fluorspar Statistics and Information. Available at: http://minerals. usgs.gov/minerals/pubs/commodity/fluorspar>.

USGS. 2003b. Mineral Commodity Summaries. Reston, Va.: USGS, 197 pp. Available at: <http://minerals.usgs.gov/minerals/pubs/mcs/>.

U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flow. 2000. Industrial Ecology Material and Energy Flows in the United States. Washington, D.C.: U.S. Government Printing Office, 95 pp.

van Beers, D., and T.E. Graedel. 2003. The magnitude and spatial distribution of in-use copper in Cape Town. South African Journal of Science 99(1/2): 61-74.

Wagner, L.A. 2002. Materials in the Economy: Materials Flows, Scarcity, and the Environment. Circular 1221. Reston, Va: U.S. Geological Survey, 34 pp.

Wilburn, D.R., and T.G. Goonan. 1998. Aggregates from Natural and Recycled Sources: Economic Assessments for Construction Applications—A Materials Flow Analysis. USGS Circular 1176. Reston, Va.: U.S. Geological Survey, 40 pp.

World Business Council for Sustainable Development. 2002. The Cement Industry Sustainability Initiative: Our Aagenda for Action. Geneva, Switzerland: World Business Council for Sustainable Development, 40 pp.

World Commission on Environment and Development (Brundtland Commission). 1987. Our Common Future. Oxford, UK: Oxford University Press, 398 pp.

Appendixes

Appendix A
Biographical Sketches of Committee Members

R. LARRY GRAYSON, *chair,* is the Union Pacific/Rocky Mountain Energy Professor of Mining Engineering and chair of the Department of Mining Engineering, School of Mines and Metallurgy at the University of Missouri-Rolla. He was formerly dean of the College of Mineral and Energy Resources at West Virginia University and chair of the West Virginia State Mine Inspectors' Examining Board (1991-1995). As the Bureau of Mines health and safety research functions were merged, he served as the first permanent associate director for the Office for Mine Safety and Health Research of the National Institute for Occupational Safety and Health, Centers for Disease Control (1997-2000). His research interests lie in mining health and safety, coal mining and coal bed methane, and other issues related to mine management and operations. His industry background is in coal mining in Pennsylvania, where he began his career as a mine laborer and surveyor, working his way through various engineering and operations positions, including mine superintendent. He is a registered professional engineer in Missouri and Pennsylvania, and a certified mine examiner and mine foreman in Pennsylvania. Dr. Grayson has served on the Board of Directors (1999-2002) of the Society for Mining, Metallurgy, and Exploration (SME), is a member of the International Society of Mine Safety Professionals, and has been chair of numerous committees and programs for SME.

DAVID T. ALLEN is the Gertz Regents Professor of Chemical Engineering and the director of the Center for Energy and Environmental Resources at the University of Texas at Austin. His research interests lie in environmental reaction engineering, particularly issues related to air quality and pollution prevention. He is the author of four books and more than 125 papers in these areas. The quality of his research has been recognized by the National Science Foundation through the Presidential Young Investigator Award, the AT&T Foundation through an Industrial Ecology Fellowship, and the American Institute of Chemical Engineers through the Cecil Award for contributions to environmental engineering. Dr. Allen was a lead investigator in the Texas air quality study, and his current research is focused on using the results from that study to provide a scientific basis for air quality management in Texas. His educational efforts have been focused on developing materials on environmentally conscious design for engineering curricula and his most recent effort is a textbook on design of chemical processes and products, developed jointly with the U.S. Environmental Protection Agency.

BRADEN ALLENBY is the environment, health, and safety Vice President for AT&T, a Batten Fellow in Residence at the University of Virginia's Darden Graduate School of Business Administration, and an adjunct professor at Columbia University's School of International and Public Affairs, Princeton Theological Seminary, and at the University of Virginia's School of Engineering. He was a telecommunications regulatory attorney at AT&T beginning in 1983 and became senior environmental attorney for AT&T (1984-1993). During 1992, he was the J. Herbert Holloman Fellow at the National Academy of Engineering. Currently, Dr. Allenby is a member of the Environmental Law Institute Board of Directors, a Resources for the Future council member, and a member of the Advisory Committee of the United Nations Environment Programme Working Group on Product Design for Sustainability. He has taught courses on industrial ecology, design for environment, and earth systems engineering and management at Yale University School of Forestry and Environmental Studies, Columbia University, Princeton Theological Seminary, and the University of the Virginia School of Engineering. Dr. Allenby is a fellow of the Royal Society for the Arts, Manufactures, and Commerce.

CORBY G. ANDERSON is the director at the Center for Advanced Mineral and Metallurgical Processing with 23 years of experience in chemical engineering, metallurgical engineering, engineering services, and plant operations. He is qualified in pyrometallurgy and mineral processing and also has industrial experience in hydrometallurgy. Dr. Anderson has been responsible for lab work, pilot plant work, research, process development, engineering design, startup, operations, management, and environmental affairs for hydrometallurgical plants producing silver, gold, antimony, nickel, cobalt, and copper. He has authored or coauthored approximately 90 papers and presentations on process technologies and holds several international patents. He is active in many professional organizations including participation as director of the Society of Manufacturing Engineers, and director of the International Precious Metals Institute, and as a trustee for the Northwest Mining Association. In 1996 he was awarded the Extraction and Processing Technology Award from the Minerals, Metals, and Materials Society. Dr. Anderson has served as a committee member and speaker for various National Research Council committees.

SCOTT R. BAKER is director of the Environment Program at the International Copper Association. Dr. Baker is a toxicologist with broad technical expertise in human health and the environment, including more than 20 years of experience directing and participating in a wide variety of scientific evaluations involving toxicology, health risk assessment, and scientific interpretation of regulatory affairs and risk management issues. Prior to his current position, he was a consulting toxicologist with Versar, Inc., and EA Engineering, Science, and Technology, after serving as science advisor to the assistant administrator for research and development at the U.S. Environmental Protection Agency (EPA). Prior to his appointment with the EPA, Dr. Baker was a senior staff officer at the National Research Council. His project experience includes scientific evaluations of the effect of chemicals on human health and the environment; assessment of the impacts of legislative initiatives, regulations, and standards; environmental toxicology investigations; and risk assessments. He has related experience in emergency preparedness, indoor air research, pesticide health effects, air toxics, and water quality criteria. Dr. Baker also has chaired and served on a number of committees and task forces related to risk assessment and environmental issues, such as chemical safety and the human health effects of chemicals.

DAVID BERRY is currently a consultant and facilitator. He initiated the Interagency Group on Sustainable Development Indicators and the Interagency Group on Industrial Ecology, both federal responses to the President's Council on Sustainable Development. The groups raise awareness of environmental, social, and economic trends; support collaboration among federal agencies; and encourage action toward sustainability. Mr. Berry was an economist in the Canadian government (Resources Canada), and a principal in a corporation using computer controls in energy management of large facilities, and ran a company in Korea trading in a wide range of materials and manufactured goods. He joined the U.S. Department of the Interior in 1991 and resigned in August 2001. Mr. Berry is on the advisory board to the International Sustainability Indicators Network and a participant in the Consulting Group on Sustainable Development Indicators. He was a U.S. delegate to the Organization for Economic Development meeting on sustainable development indicators in Rome in 1999 and led a U.S. team on information for decision making at the meetings of the Commission on Sustainable Development Ninth Session

United Nations meetings in 2001. He has spoken in many countries on sustainability and appeared on Korean and American television and public radio.

ROBERT COSTANZA is Gund Professor of Ecological Economics and director of the Gund Institute of Ecological Economics at the School of Natural Resources at the University of Vermont. He was professor and director of the University of Maryland Institute for Ecological Economics, Center for Environmental Science at Solomon's and College Park, Maryland, for more than 10 years. He also was a professor in the Department of Biology at the University of Maryland, College Park. Dr. Costanza's research interests and areas of expertise include systems ecology, ecological economics, environmental policy, landscape ecology, ecological modeling, energy analysis, social traps, incentive structures, and institutions. He has co-authored or authored more than 100 journal articles and 17 books. Dr. Costanza is co-founder and past vice president and president of the International Society for Ecosystem Health. He is also an active member of the Ecological Society of America, the American Association for the Advancement of Science, and the International Society for Ecological Modeling. His accomplishments have been recognized through several awards and honors, including a Pew Scholarship (1993-1996) and a Kellogg National Fellowship (1982-1985).

THOMAS E. GRAEDEL is a professor of industrial ecology, of chemical engineering, and of geophysics at Yale University's School of Forestry and Environmental Studies. For more than 30 years he has studied both chemical kinetic modeling of gases and droplets in Earth's atmosphere and corrosion of materials by atmospheric species. Dr. Graedel's current interest is focused on industrial ecology, especially the flows of materials through the technological society and their potential environmental implications. He has authored 11 books and more than 250 technical papers. Dr. Graedel is a member of the National Science Foundation Advisory Committee on Environmental Research and Education, and chair of the International Society for Industrial Ecology Awards Committee. He has received several honors and awards in recognition of his accomplishments, including American Association for the Advancement of Science and American Geophysical Union fellowships and election to the National Academy of Engineering.

JOYCE SEE-YIN LEE is the chief architect at the New York City Office of Management and Budget (OMB). In the City Chartered Asset Management Program, she oversees the effort of consultants and in-house staff in the survey of major public buildings, including libraries, schools, courthouses, police precincts, firehouses, hospitals, health centers, museums, and cultural facilities. She supervises the production of citywide reports identifying state of good repair needs on behalf of the Mayor. In her capacity at OMB, Ms. Lee also oversees resource-efficient design and construction citywide. She conducts energy and resource efficiency reviews of capital projects and raises the awareness of sustainable design and construction practices within the public sector. She works with construction and operating agencies, the mayor's offices, state authorities, and a university consortium to broaden educational opportunities as well as to address financial issues in sustainable development. In 1998, she founded the Committee on the Environment at the American Institute of Architects New York Chapter. She is now national chair of the AIA Committee on the Environment

WAYNE B. TRUSTY is president of the ATHENA™. Sustainable Materials Institute, having served as project manager of the predecessor ATHENA™ Project (1991-1997). In addition, Mr. Trusty is also a private consultant, having started his own consulting practice in 1972 after gaining experience with such organizations as Acres Consulting Services and Stanford Research Institute. He has worked with private industry and government on a range of assignments that cover a wide spectrum of subjects including the environment, forest industry economics and forest policy, water resources, transportation, energy policy and markets, and regional development. He has also served as economic adviser on several large projects, including the Canadian Arctic Gas Pipeline project, and has appeared as an expert witness before regulatory bodies in Canada and the United States. He is a member of several organizations, including the Technical Committee of the U.S. Consortium for Research on Renewable Industrial Materials, the U.S. Green Building Council, Society of Environmental Toxicology and Chemistry, and Construction Industry Board. He is a past chairman of an International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) technical committee examining the use of Life Cycle Assessment with regard to building materials and products.

DIRK J.A. VAN ZYL is professor of mining engineering and director of the Mining Life-Cycle Center at the Mackay School of Mines at the University of Nevada, Reno. He is also a geotechnical and environmental mining consultant. In this role, he provides consulting services to the mining industry with emphasis on mine waste management and heap leach facility design and mine closure. During his professional career, he has held the positions of engineer, professor, vice president, and president. He has authored or coauthored more than 60 papers. Dr. Van Zyl's work has been recognized through the J.E. Jennings Award from the South African Institute of Civil Engineers, as well as through multiple awards from the Society for Mining Metallurgy and Exploration, Inc. He is an active member of the American Society of Civil Engineers, the Society for Mining, Metallurgy, and Exploration, and a registered professional engineer in 11 states.

NRC STAFF

TAMARA L. DICKINSON, *study director*, is a senior program officer with the National Research Council's Board on Earth Sciences and Resources, responsible for managing the earth resources activities of the Board. Dr. Dickinson was awarded the National Academies individual distinguished service award in 2002. She has served as program director for the Petrology and Geochemistry Program in the Division of Earth Sciences at the National Science Foundation. She has also served as discipline scientist for the Planetary Materials and Geochemistry Program at National Aeronautics and Space Administration (NASA) Headquarters. As a postdoctoral fellow at the NASA Johnson Space Center, she conducted experiments on the origin and evolution of lunar rocks and highly reduced igneous meteorites. She holds a Ph.D. and an M.S. in geology from the University of New Mexico and a B.A. in geology from the University of Northern Iowa.

KAREN L. IMHOF is a senior project assistant for the Board on Earth Sciences and Resources of the National Research Council. She previously worked on the Board on Agriculture and Natural Resources. Before coming to the Academies, she worked as a staff and administrative assistant in diverse organizations, including the National Wildlife Federation, the Lawyers' Committee for Civil Rights Under Law, and the Three Mile Island nuclear facility.

MONICA R. LIPSCOMB is a research assistant for the National Academies Board on Earth Sciences and Resources. She has completed her coursework for a master of urban and regional planning degree at Virginia Polytechnic Institute, with a concentration in environmental planning. Previously, she served as a Peace Corps volunteer in Côte d'Ivoire and has worked as a biologist at the National Cancer Institute. She holds a B.S. in environmental and forest biology from the State University of New York, Syracuse.

Appendix B
Information Provided to the Committee

SPEAKERS AT COMMITTEE MEETINGS

Frederick Allen, U.S. Environmental Protection Agency, Washington, D.C.
Patrick Atkins, Alcoa, New York, New York
John Carberry, DuPont, Wilmington, Delaware
Kenneth Friedman, U.S. Department of Energy, Washington, D.C.
William Gager, The Remanufacturing Institute, Chantilly, Virginia
Chris Hendrickson, Carnegie Mellon University, Pittsburgh, Pennsylvania
Kathleen Johnson, U.S. Geological Survey, Reston, Virginia
Gregory Mella, SmithGroup/LEED™, Washington, D.C.
Drew Meyer, Vulcan Materials, Birmingham, Alabama
Yuichi Moriguchi, National Institute for Environmental Studies, Tokyo, Japan
Sumiye Okubo, Bureau of Economic Analysis, Washington, D.C.
Andrew Opperman, New Jersey Department of Environmental Protection, Trenton, New Jersey
Donald Rogich, (consultant), World Resources Institute, Washington, D.C.
Matthias Ruth, University of Maryland, College Park, Maryland
Anton Steurer, Eurostat, Luxembourg
Leonard Surges, Noranda, Ontario, Canada
Tom Tyler, Institute of Scrap Recycling Industries, Washington, D.C.
Herman Zimmerman, National Science Foundation, Arlington, Virginia

Appendix C
Detailed Classification of Material Inputs*

Domestic extraction (used)

Fossil fuels

Hard coal

Lignite (brown coal)

Crude oil

Natural gas

Other (crude oil gas, peat for combustion, oil shale, etc.)

Minerals

Metal ores

Iron ores

Nonferrous metal ores

Bauxite

Copper ores

Other

Industrial minerals

Salts

Special clays

Special sands

Peat for agricultural use

Other

Construction minerals

---

*From Table 6, Economy-Wide Material Flow Accounts and Derived Indicators: A Methodological Guide (Eurostat, 2001).

Sand and gravel
Crushed stones (including limestone for cement making)
Common clays (for brick making, etc.)
Dimension stones
Other

Biomass *(including biomass extracted for own final use)*

Biomass from agriculture

Biomass from agriculture reported by harvest statistics

Cereals
Roots and tubers
Pulses
Oil crops
Vegetables
Fruits
Tree nuts
Fiber crops
Other crops

Biomass from agriculture as a by-product of harvest

Crop residues used as fodder
Straw used for economic purposes

Biomass from grazing of agricultural animals

Grazing on permanent pastures not harvested
Grazing on other land (including alpine pastures)

Biomass from forestry

Wood

Coniferous
Nonconiferous

Raw materials other than wood

Biomass from fishing

Marine fish catch
Inland waters (freshwater) fish catch
Other (aquatic mammals and other)

Biomass from hunting

Biomass from other activities (honey, gathering of mushrooms, berries, herbs, etc.)

Imports[1]

Raw materials

Fossil fuels
Minerals

---

[1]Import (and export) data should be organized at a more detailed level in parallel to the classification of domestic extraction to the extent possible, to allow aggregation.

Biomass
Secondary raw materials
Semimanufactured products
From fossil fuels
From minerals
From biomass
Finished products
Predominantly from fossil fuels
Predominantly from minerals
Predominantly from biomass
Other products
Other products of abiotic kind
Other products of biotic kind
Other products national emissions ceiling
Packaging material imported with products
Waste imported for final treatment and disposal

Memorandum items for balancing[2]
Oxygen for combustion (of Carbon, Hydrogen, Sulfur, Nitrogen, etc.)
Oxygen for respiration
Nitrogen for emissions from combustion
Air for other industrial processes (liquefied technical gases, polymerization, etc.)

Unused domestic extraction[3]
Unused extraction from mining and quarrying of fossil fuels
Unused extraction from mining and quarrying of minerals
Unused biomass from harvest
Wood harvesting losses
Agricultural harvesting losses
Other (discarded by-catch, etc.)
Soil excavation and dredging
Excavation for construction activities
Dredging materials

[2]Memorandum items for balancing are not to be included when compiling indicators.
[3]Soil erosion could be shown as an optional memorandum item of unused domestic extraction and unused extraction associated with imported products but is not to be included when compiling indicators.

Indirect flows associated to imports

Raw material equivalent of imported products[4]

Fossil fuels
Minerals
Biomass

Unused extraction of imported products[3]

Unused extraction from mining and quarrying of fossil fuels
Unused extraction from mining and quarrying of minerals
Unused biomass from harvest
Soil excavation and dredging

[4]The indirect flows (of used materials) are compiled as raw material equivalents minus the weight of the imports.

Appendix D
Detailed Classification of Material Inputs*

Emissions and wastes

Emissions to air *from combustion and industrial processes*

CO_2
SO_2
NO_x as NO_2
Volatile Organic Compound (Non-methane Volatile Organic Compound excluding solvents and CH_4 excluding CH_4 from landfills)
CO
Particulate matter (including dust)
N_2O excluding use of products and N from agriculture and wastes
NH_3 excluding N from fertilizers
Chlorinated Fluorocarbons and Halons

Waste landfilled

From private households (and household-type waste from industry and commerce)
From industry and commerce (production waste and Construction or demolition waste)
From waste and wastewater management activities (sewage sludge, etc.)

Emissions to water

Nitrogen (N)
Phosphorus (P)
Other substances and (organic) materials
Dumping of materials at sea

---

*From Table 8, Economy-Wide Material Flow Accounts and Derived Indicators: A Methodological Guide (Eurostat, 2001).

Dissipative use of products and dissipative losses

Dissipative use of products

Dissipative use on agricultural land

Mineral fertilizers

Farmyard manure

Sewage sludge

Compost

Pesticides

Seeds

Dissipative use on roads (thawing and grit materials)

Dissipative use of other kind (including solvents)

Dissipative losses

Abrasion (tires, etc.)

Accidents with chemicals

Leakages (natural gas, etc.)

Erosion and corrosion of infrastructures (roads, etc.)

Exports[1] (detailed classification is the same as for imports)

Memorandum items for balancing[2]

Water vapor from combustion (H_2O)

From water (H_2O) contents of fuels

From hydrogen (H) contents of fuels

Water evaporation from products

Water content of biomass

Water content of other materials

Respiration of humans and livestock

CO_2

Water vapor (H_2O)

Disposal of unused domestic extraction (same detailed classification as for unused domestic extraction)[3]

Indirect flows associated to exports (same detailed classification as for indirect flows associated to imports)[3]

---

[1]Export data should be organized at the same level of detail as imports to the extent possible, to allow compilation of physical trade balances by material groups.

[2]Memorandum items for balancing are not to be included when compiling indicators.

[3]Soil erosion could be shown as an optional memorandum item of disposal of unused domestic extraction and unused extraction associated with imported products but is not to be included when compiling indicators.

Appendix E
Classification of Material Stock Changes*

Total (gross) additions
- ***Infrastructures and buildings***
  - Construction minerals
  - Metals
  - Wood
  - Other construction materials
- ***Other (machinery, durable goods, etc.)***
  - Metals
  - Other materials

Removals (including losses)
- ***Infrastructures and buildings***
  - By demolition
    - Construction minerals
    - Metals
    - Wood
    - Other materials
  - By dissipative loss
    - Construction minerals
    - Metals
    - Wood
    - Other materials

*From Table 9, Economy-Wide Material Flow Accounts and Derived Indicators: A Methodological Guide (Eurostat, 2001).

Other (machinery, durable goods, etc.)
By discard
Metals
Other materials
By dissipative loss
Metals
Other materials

Net additions to material stock (gross additions minus removals)
Infrastructures and buildings
Construction minerals
Metals
Wood
Other materials
Other (machinery, durable goods, etc.)
Metals
Other materials

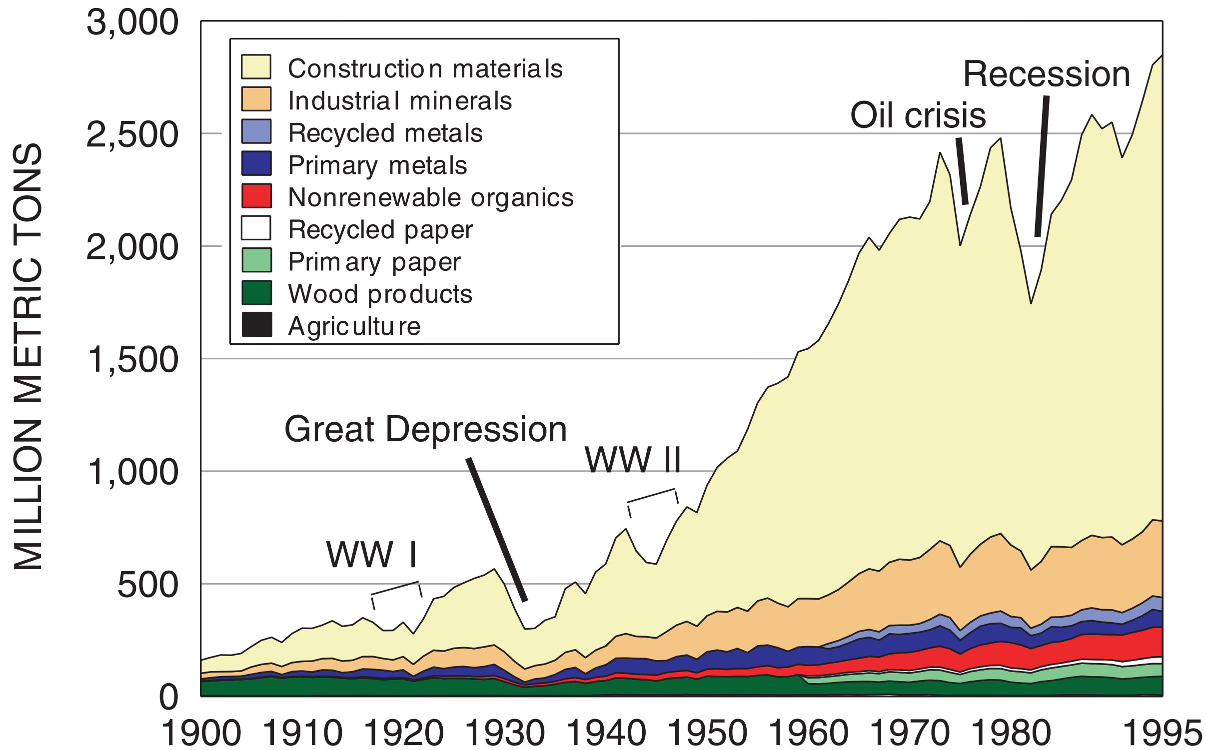
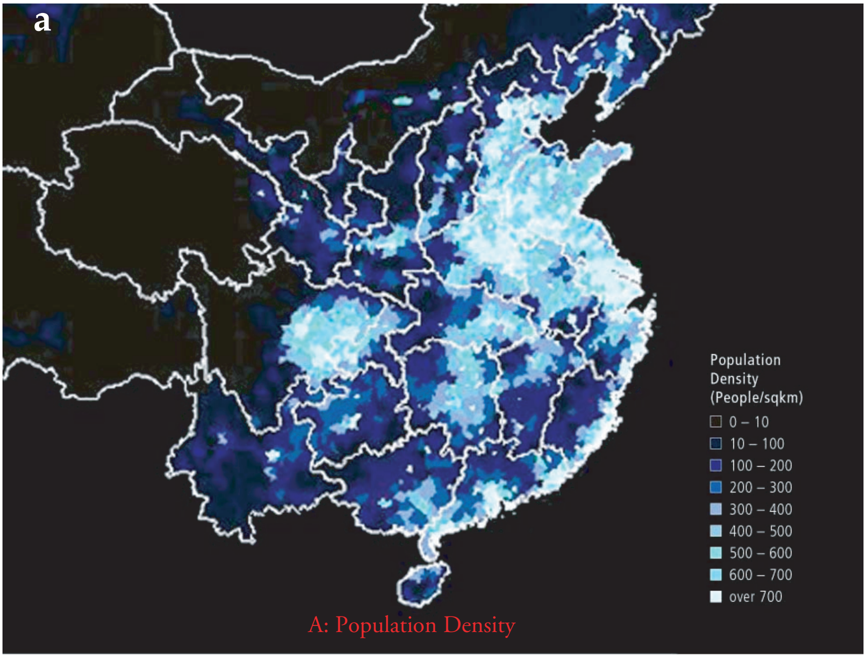
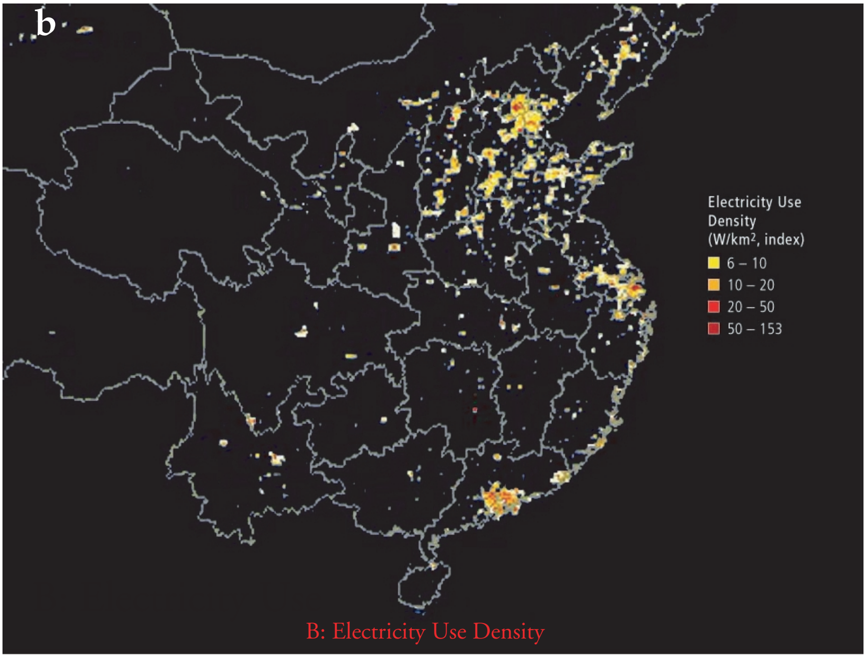


PLATE I Measurement of the raw materials consumed in the United States, 1990 to 1995. WWI, World War I; WWII, World War II.
SOURCE: Matos and Wagner, 1998, p. 3.



A: Population Density



B: Electricity Use Density

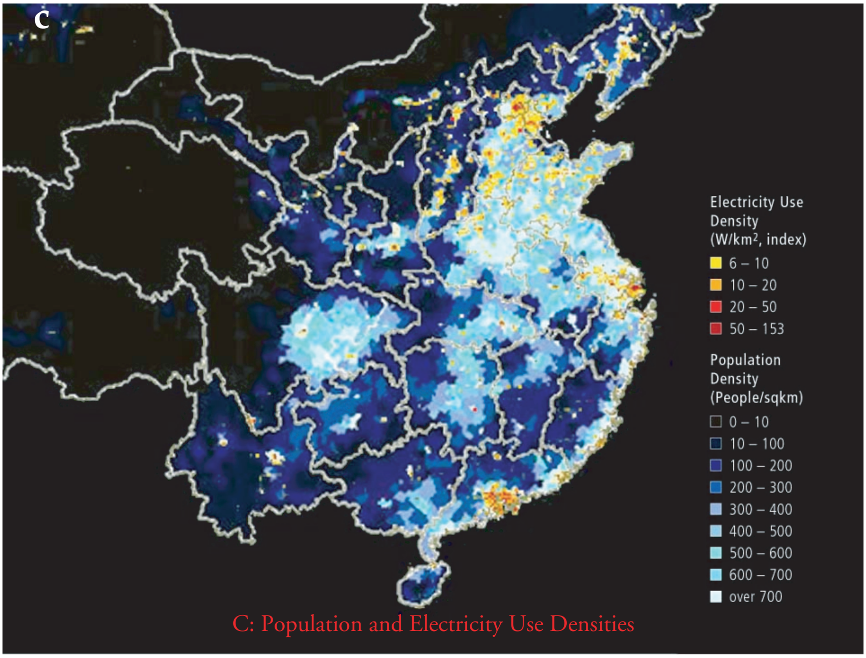
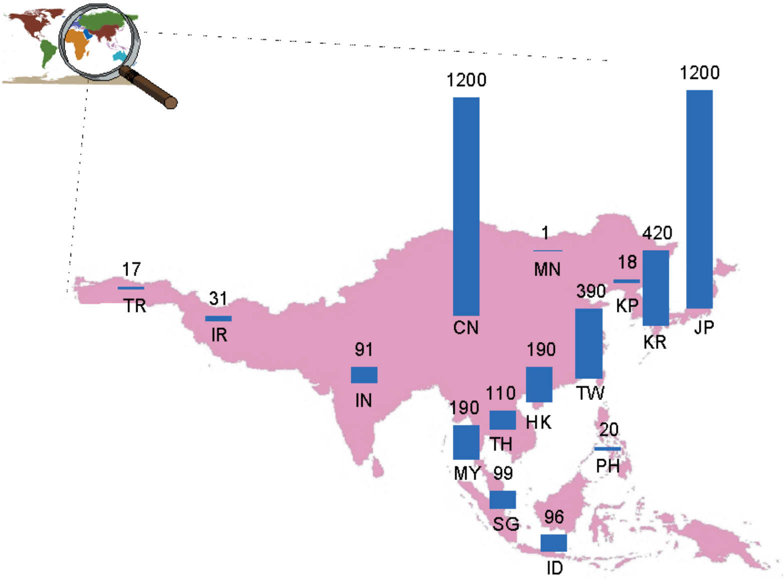


PLATE II Comparison of energy use and population density in China: (a) spatial population in China; (b) light emitted from energy-utilizing activities as monitored by satellite; (c) images a and b combined. SOURCE: Figure courtesy of A. Grübler and S. Prieler, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. Primary data sources used to derive the graphs include disaggregated population density distributions assembled by the Land Use Change project at IIASA, and night-time luminosity data provided by C. Elvidge, National Oceanic and Atmospheric Administration.



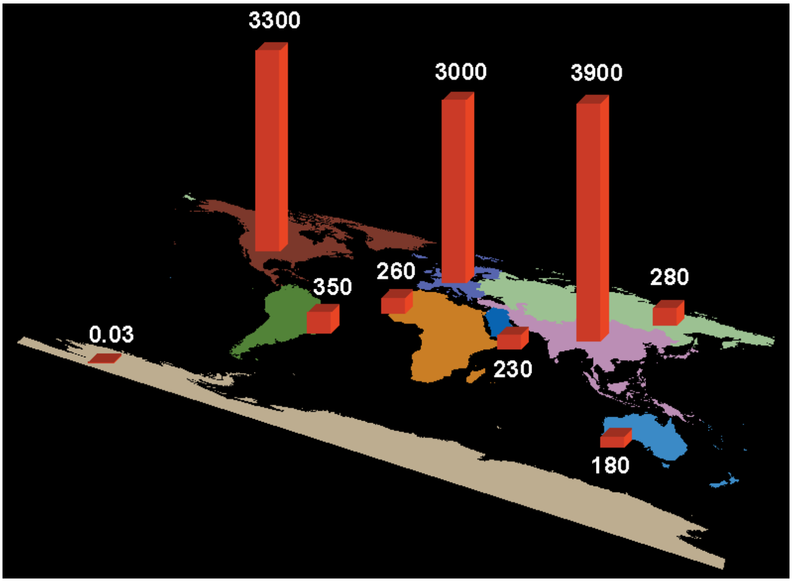


PLATE III Contemporary copper cycle on several spatial levels: (a) comparative annual rates of copper entering use in Asian countries around 1994. (b) comparative annual rates of copper on a regional basis shown on the world map. SOURCE: Graedel et al., 2003. Copyright permission granted by Yale University.