# Indicators of Dematerialization and the Materials Intensity of Use

Cutler J. Cleveland
Matthias Ruth
*Center for Energy and Environmental Studies and Department of Geography*
*Boston University*
*Boston, MA, USA*

**Keywords**
dematerialization
Divisia index
environmental Kuznets curve
environmental metrics
intensity of use (IU)
materials efficiency

## Summary

We review the major empirical analyses of the related concepts of dematerialization and intensity of use. Dematerialization refers to the absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output. A common indicator is the intensity of material use, which is the quantity of material used per unit of economic output. Our discussion focuses on seven topics: the environmental Kuznets curve for materials, material use and long wave theory, material decomposition analysis, statistical, input-output and dynamic models of material use, and analyses of national material use. We examine the measurement of aggregate material use and waste emissions, hypothesis testing, the importance of imports, and forces that countervail dematerialization such as rising affluence and the "rebound effect." We conclude that: our knowledge of the extent of and mechanisms behind the patterns of material use are limited largely to individual materials or very specific industries, and most of those examples are metals; the economy is getting "lighter," but the aggregate economic significance of that trend, if any, is unknown; there is no compelling macroeconomic evidence that the U.S. economy is "decoupled" from material inputs; and we know even less about the net environmental effects of many changes in materials use. We caution against gross generalizations about material use, particularly the "gut" feeling that technical change, substitution, and a shift to the "information age" inexorably lead to decreased materials intensity and reduced environmental impact. We end with some suggestions for research that may help answer these important questions.

**Address correspondence to:**
Cutler Cleveland
Center for Energy and Environmental Studies and Department of Geography
Boston University
675 Commonwealth Avenue
Boston, MA 02215, USA
cutler@bu.edu
http://web.bu.edu/CEES/

Volume 2, Number 3

## Introduction

The study of materials use in economic systems has a rich history, although the emphasis has shifted with changing perceptions of national security and economic and environmental imperatives. Early work concentrated on issues of the adequacy of raw material supplies to meet economic and national security needs. The seminal work in the United States by the President's Materials Policy Commission (1952) was concerned with "soaring demands, shrinking resources, the consequent pressure towards rising real costs, the risk of wartime shortages, [and] the ultimate threat of an arrest or decline in the standard of living we cherish and hope to help others to attain" (p. 1). In the *Limits to Growth* (Meadows et al. 1972) era, continuing concern for the adequacy of material supplies was coupled with growing concern about the effects of material wastes on the health of people and ecosystems. With a long history of interest in basic materials research and the role of materials in technology, engineers expanded their interest to include the critical role of technology in mediating the efficiency of materials use and the release of material wastes in production and consumption (Ausubel and Sladovich 1989). The current phase of this evolution includes industrial ecology (Graedel and Allenby 1995) and industrial metabolism (Ayres 1989a), which seek a full accounting of the energy and material flows that drive economic production and that link society to the planet's grand material cycles. The growing body of work on sustainability indicators includes a variety of material metrics (OECD 1994; Hammond et al. 1995; Moldan and Billharz 1997).

Dematerialization has been an important thread throughout this work for the past quarter century. Definitions vary (figure 1), but in general, dematerialization refers to the absolute or relative reduction in the quantity of materials used and/or the quantity of waste generated in the production of a unit of economic output. There has been a steady stream of research that suggests that the U.S. economy has dematerialized (Carter 1966; Malenbaum 1978; Larson et al. 1986; Jänicke et al. 1989; Hinterberger et al. 1997). Many attribute this to a "natural" or "evolutionary" process driven by the maturation of economies or rising incomes (Ayres 1989a; Bernardini and Galli 1993; Grübler 1994a). The apparent dematerialization leads some to hypothesize that the human economy can decouple itself from energy and material inputs by a factor of ten (Factor 10 Club 1997).

Other analysts have a less sanguine interpretation of the historical record for a number of reasons, which we summarize here and then return to in greater detail later in the article. First, aggregate material use[1] often is measured in terms of weight, which when compared with gross national product (GNP) in an index of the "efficiency" of material use probably has little economic meaning because weight is only one of many attributes that users consider when choosing materials. Thus, weight is an inappropriate basis for the aggregation of materials. Second, many analyses of dematerialization do not explicitly represent demand, technological change, or structural change (e.g., the effects of a shift from manufacturing to services on materials use), and they do not use methodologies that can test for the presence and relative strength of these forces (Auty 1985). Third, the techniques used to test for "trends" in time series and cross-sectional data often lack statistical rigor, with a few notable exceptions. Fourth, a reduction in the quantity (weight) of material use per unit output is not necessarily better from an environmental perspective because every change in the pattern of material use has a unique impact on the quantity and quality of waste generation (Herman et al. 1989). Fifth, little attention has been paid to the "rebound effect," the potential for improvements in efficiency to actually increase material use. Finally, although the efficiency of use of individual materials could rise, overall aggregate economic growth could increase total material consumption.[2] Thus, although there is a wealth of studies that document improvements in the use of individual materials, we have a much less complete picture of the pattern and implications for broader classes of materials and for aggregate material use.

We focus on the use of materials as inputs to

### Definitions of Dematerialization

"...dematerialization refers to the absolute or relative reduction in the quantity of materials required to serve economic functions" (Wernick et al. 1996, 171).

"...the decline over time in the weight of the materials used in industrial end products" (Herman et al. 1989, 50).

"...the change in the amount of waste generated per unit of industrial products" (Herman et al. 1989, 51).

"...the reduction of raw material (energy and material) intensity of economic activities, as measured as the ratio of material (or energy) consumption in physical terms to gross domestic product (GDP) in deflated constant terms" (Bernardini and Galli 1993, 432).

"Instead of a once and for all structural change, as implied by dematerialization, minerals demand experience phases in which older, transmaterialization suggests that lower quality materials linked to mature industries undergo periodic replacement by higher quality or technologically more appropriate materials" (Labys and Waddell 1989, 238).

**Figure 1** Definitions of dematerialization.

production, reflecting the emphasis of most studies of dematerialization and intensity of use. Many studies implicitly assume that materials consumption is a good proxy for environmental degradation caused by the release of material wastes. We briefly discuss this assumption, leaving a more complete analysis for future research.

The purpose of this analysis is threefold. First, in the two sections that immediately follow we review the major empirical analyses of dematerialization, focusing on their assumptions, indicators, and key results. The central element of this work is the intensity of material use (IU), which is the quantity of material used per unit of economic output. Second, in the next seven sections, we discuss the major strengths and weaknesses of the research, with an eye toward what future research needs to focus on. Finally, in the concluding section, we pose some specific unanswered questions that could help shape the future research agenda in dematerialization. The focus here is on the United States, where the bulk of the work has been done, although a number of the studies reviewed include the United States in international comparisons.

## Concept and Meaning of Intensity of Use

The most widely used measure of the quantity of material used to produce goods and services is the IU, which is often intended to be a summary measure that links the use of a material(s) to trends in the output of an industry, sector, or economy. Empirical measures of IU are derived from the accounting identity that defines the consumption of a specific material $i$ ($X_i$):

$$X_i = \left(\frac{X_i}{Y}\right)\left(\frac{Y}{\text{GNP}}\right)(\text{GNP}) \qquad (1)$$

where $Y$ is the output of industries that consume material $i$, and $GNP$ is the total output of the economy. IU typically is defined as the ratio of materials use to value added, which in the case of an economy is equivalent to gross domestic product (GDP) (Tilton 1990; Considine 1991):

$$\mathrm{IU} = \frac{X_i}{\mathrm{GNP}} = \left(\frac{X_i}{Y}\right)\left(\frac{Y}{\mathrm{GNP}}\right) \qquad (2)$$

Most analyses of IU measure $X$ in physical units (weight or volume) and aggregate different materials on this basis (table 1). This raises a number of important conceptual and methodological issues that we return to in later sections.

IU is determined by two quantities. The first term on the righthand side of equation (2) is the material composition of product, which reflects changes in the mix of materials used to produce individual goods. The second term is the product composition of output, which reflects changes in the mix of goods produced by the economy.

Changes in these two factors, and hence changes in IU, are determined by a number of social, economic, technological, institutional, and environmental forces. Those identified in the literature include the following:

- Technical improvements that decrease the quantity of materials used to produce a good or service. Well-documented examples include metal use in the beverage container industry (Nappi 1990), materials use in automobile manufacture (Larson et al. 1986), and communications (Key and Schlabach 1986). Technical changes that improve material efficiency include not only advances in engineering and materials science, but also in the organization and management of production itself, such as computer-aided production processes and just-in-time production (Devine 1988; Bernardini and Galli 1993).
- Substitution of new materials with more desirable properties for older materials. Key and Schlabach (1986) identify four categories of intermaterial substitution: cost driven (aluminum for copper in electrical conductors), availability driven (other metals for cobalt), regulatory driven (lighter for heavier materials in cars), and functionality driven (optical fibers for metal wire in communications). More general economy-wide examples include the substitution of coal, oil, and natural gas for wood as a fuel source (Nakicenovic 1996) and the substitution of iron and steel, aluminum, cement, and plastic for wood as a construction material.
- Changes in the structure of final demand. The mix of goods and services produced and consumed by an economy change over time due to shifts among sectors, such as the rise of the service sector, or shifts within sectors, such as the increasing dominance of computers and other high-technology goods within the manufacturing sector. The general assumption is that the shift toward services and “high-tech” or “knowledge-intensive” products reduces the quantity of material required to produce a dollar’s worth of output (Bernardini and Galli 1993; Jänicke et al. 1997). Changes in people’s preferences also could lead to an increased emphasis on the nonmaterial aspects of consumer satisfaction.
- The saturation of bulk markets for basic materials. This line of reasoning holds that as an economy matures, there is less demand for new infrastructure such as bridges, roads, railways, steel factories, and so on, reducing the need for steel, cement, and other basic materials.
- Government regulations that alter materials use. A prominent example in the United States is the regulation of lead additives in gasoline and other products that contributed to a sharp decline in the IU of lead.

There are other variables that determine the IU of a material, and the ones described above are not independent of each other. For example, technical changes often are accompanied by materials substitution, and it is difficult to separate the two effects in empirical analysis. However, most of the empirical work on dematerialization focuses on these driving forces.

## Theory and Empirical Analysis of IU

The purpose of this section is to review the principal studies of dematerialization. Given the diversity of materials, perspectives, and approaches, one could pick any number of themes to organize the discussion. To as large extent as

**Table 1** Studies of the materials intensity of use (IU)

| *Study* | *Region* | *Sector(s)* | *Time period* | *Index* | *Comments* |
|---|---|---|---|---|---|
| **Materials EKC** | | | | | |
| Brooks and Andrews (1974) | U.S.<br>Canada | Copper and aluminum | 1926–71 | Weight/GDP | IU for copper shows inverted U shape<br>IU for aluminum shows rising trend with rate of increase declining at end of period |
| Radcliffe (1976) | U.S. | Wood products | 1900–72 | Weight/person | IU declines for total products and lumber<br>IU rises for pulpwood and veneer |
| Malenbaum (1978) | 10 global regions | 12 nonfuel minerals | 1955–75 | Weight/GDP | Inverted U-shaped path for IU as function of GDP for 10 of 12 materials |
| Williams et al. (1987)<br>Larson et al. (1986) | U.S. | Steel, cement, paper, ammonia, chlorine, aluminum, ethylene | 1890–85 (dates vary by material) | Weight/GNP; weight per capita | IU show inverted U shape as function of income; timing varies between “old” and “new” materials |
| Jänicke et al. (1989) | 31 nations | Steel, energy, cement, and the weight of freight transport | 1970–85 | Average of deviations from the mean weight per capita of each index | “Delinking” occurred between material inputs and economic growth for many nations; some eastern European nations showed increasing IU |
| Jänicke et al. (1997) | 32 nations | 9 materials; petroleum products; electricity | 1970–91 | Weight/GNP; weight per capita; absolute growth in materials compared to GDP | IU generally falls w/ rising income for some materials (cement) but rises for others (paper) |
| Rogich (1993b) | U.S. | Total material use; broad material aggregates | 1970–89 | Weight per capita; volume per capita | Weight-based IU falls w/ income;<br>Volume-based IU rises w/ income |

**Table 1** (continued)

| *Study* | *Region* | *Sector(s)* | *Time period* | *Index* | *Comments* |
|---|---|---|---|---|---|
| Grübler and Fujii (1991) | U.S. | Carbon release from aggregate energy use | 1900–88 | kg carbon/GDP | IU shows threefold decline |
| Grübler (1994b) | 6 nations | Carbon release from aggregate energy use | 1900–88 | kg carbon/ industrial GDP | IU shows decline as function of industrial GDP/capita |
| de Bruyn and Opschoor (1997) | 20 nations | Steel, energy, cement, and the weight of freight transport | 1966–90 | Average of deviations from the mean of weight per capita of each index | IU shows an "N shape" as function of income |
| **Long wave theory** | | | | | |
| Fisher and Pry (1971) | U.S. | 17 cases of materials substitution | 1920–60s | Market share capture by material | Logistic function describes market share of material over time |
| Williams et al. (1987)<br>Larson et al. (1986) | U.S. | 7 secondary materials;<br>10 metals;<br>aggregate index of 25 materials | 1900–85 (dates vary by material) | Weight/GNP: weight per capita | IU (GNP) for individual materials and broad groups show inverted U shape;<br>IU (per capita) show logistic-type growth, or may eventually decline |
| Labys and Waddell (1989) | U.S. | 28 materials;<br>5 aggregate materials groups | 1930–85 | Weight/GNP | IU for individual materials and broad groups show inverted U shape as function of time |
| Roberts (1992) | U.S. | Aluminum, copper, lead, zinc | 1950–mid-1980s | IU: weight/can; market share: % of market | IU shows exponential decline via learning curve; logistic function describes market share of technology over time |

**Table 1** (continued)

| *Study* | *Region* | *Sector(s)* | *Time period* | *Index* | *Comments* |
|---|---|---|---|---|---|
| Roberts (1996) | Global | Aluminum, copper, lead, zinc | 1950–93 | Weight/GDP | Uses quadratic model to represent inverted U shape for IU as function of income in regression analysis to explain metal consumption; IU declines for all metals |
| Fortis (1994) | U.S. | Cotton, lead, lumber, pig iron, copper, zinc, steel, wood pulp, rubber, aluminum | 1860–1990 | Index of material demand/index of industrial production | IU for materials show successive, overlapping bell-shaped curves |
| **Materials decomposition analysis** | | | | | |
| Roberts (1988) | World | 8 major metals | 1960–84 | Weight/GDP | IU declines for most metals; IU for aluminum increases |
| Roberts (1990) | U.S. | Steel use in machinery and metal products, transport equip, and infrastructure | 1963–83 | Weight/value product produced | IU declines in all uses |
| Considine (1991) | U.S. | Steel, copper, aluminum, plastic use in sheet, strip, pipe, and wire products | 1960–85 | Divisia index of materials use/value of output | Steel and copper IU decline;<br>plastic and aluminum IU increase;<br>aggregate IU shows no overall trend |
| Waggoner et al. (1996) | U.S. | Paper and lumber | 1904–90 | Weight/GNP | IU for paper grew 0.9% per year;<br>IU for lumber fell 2.8% per year |
| Wernick et al. (1997) | U.S. | Industrial roundwood products | 1900–93 | Volume/GDP | IU declined at an average annual rate of 2.5% |

**Table 1** (continued)

| *Study* | *Region* | *Sector(s)* | *Time period* | *Index* | *Comments* |
|---|---|---|---|---|---|
| **Regression analysis** | | | | | |
| Ross and Purcell (1981) | U.S. | 6 materials | 1950–78 | Weight/industrial GDP | IU for lumber, steel, cement declined sharply; chemicals increasing slowly |
| Humphreys (1994) | U.K. | Nonferrous metals; construction materials | 1960–92 | Dollar value of material consumption divided by GDP | Metal intensity drops 60%; construction materials intensity "shows no evident trend" |
| Labson and Crompton (1993) | U.S., Japan, U.K., OECD | Steel, copper, lead, zinc, and tin | 1946–89 (varies by material/ region) | Weight | Little evidence for a long-run equilibrium relationship between income and metals consumption |
| Labson (1995) | U.S., Japan, U.K., OECD | Steel, copper, lead, zinc, and tin | 1946–93 (varies by material/ region) | Weight/GDP | OECD steel, tin, and zinc demand does follow in "lockstep" with income |
| Moore et al. (1996) | U.S. | Nonferrous metals; construction materials | 1960–92 | Dollar value of material consumption divided by GDP | IU declines for both material groups |
| **Input-output analysis** | | | | | |
| Carter (1966) | U.S. | 9 material aggregates | 1947–58 | Value of materials | Decline in the IU of materials and semifinished goods |
| Leontief et al. (1983) | U.S. | 18 metals<br>8 nonmetals | 1972–2000 | Physical quality of material per dollar output | IU for most metals forecast to decline;<br>IU for most nonmetals forecast to increase |
| Duchin and Lange (1994) | 16 region world model | 6 metals | 1980s | Value of material per dollar of output | IU declined for most metals in most regions;<br>IU increased for zinc and aluminum |

**Table 1** (continued)

| *Study* | *Region* | *Sector(s)* | *Time period* | *Index* | *Comments* |
|---|---|---|---|---|---|
| **Visual inspection of data** | | | | | |
| Fischman (1980) | U.S., Japan, Russia, Sweden, Italy, Germany, France | Aluminum, copper, lead, zinc, manganese, chromium | 1960–77 | Weight/GNP (5-year moving average) | Chromium: varies by nation;<br>aluminum: increases in all nations;<br>copper: declines in most nations; increase in Japan; no trend in Russia;<br>zinc: varies by nation;<br>lead: declines in most nations |
| Key and Schlabach (1986) | U.S. telecomm. | Aluminum, copper, lead, steel | 1955–84 | Weight per dollar of sales of telecommunications products | IU generally falls for all materials |
| Hutchinson and Tilton (1987) | U.S. | Copper | 1900–85 | Weight/GNP | Overall inverted U shape with steady decline since 1940s; adjusting IU for imports in goods and for scrap consumption suggests IU no longer falling |
| Cochran (1988) | U.S. | Consumption of 9 old and new materials | 1850–1980s | Volume consumed; real price | Relative prices per unit volume drive substitution; total volume consumed increases |
| Tilton (1990) | OECD, EEC, Japan, U.S., U.K., Germany, France | Steel, aluminum, copper, lead, zinc, nickel | 1960–87 | Weight/GNP | OECD: IU rises 1960–73, then falls after 1973 for many metals;<br>EEC: IU generally falls 1960–87 |

**Table 1** (continued)

| *Study* | *Region* | *Sector(s)* | *Time period* | *Index* | *Comments* |
|---|---|---|---|---|---|
| **Analyses of aggregate national material use** | | | | | |
| Spencer (1980) | U.S. | Total material, energy, and food use; broad aggregates | 1900–77 | Total value of materials; value of materials use/person;<br>GNP/value of materials | Ratio of GNP to materials use increased by factor of 3 |
| Wernick (1994) | U.S. | 6 individual materials | 1900–90 | Weight/GDP | IU for plastic and aluminium generally increases<br>IU for lead, steel, and lumber declines |
| Wernick et al. (1996) | U.S. | Total material use; 9 specific materials | 1900–90 | Weight/GDP | Overall IU declines by 1/3 since 1970; individual materials show increasing and decreasing IU |
| Rogich (1996b) | U.S. | Total material use; broad material aggregates | 1970–89 | Weight/GNP;<br>weight per capita;<br>volume/GNP;<br>volume per capita; | Weight-based IU declines for total materials:<br>IU for plastics increases |
| Bringezu (1997) | Germany | Most major material and energy inputs (DMI); “hidden” flows mobilized by mining, erosion, building, etc. | 1975–94 | GDP/weight | Material productivity increases from 1975–1987, declines modestly thereafter |
| Adriaanse et al. (1997) | U.S., Germany, Japan, Netherlands | Most major material and energy inputs (DMI); “hidden” flows mobilized by mining, erosion, building, etc. | 1975–94 | Weight/GDP | IU for direct plus hidden material inputs shows “modest” decline;<br>IU for direct materials input declines but levels off beginning in 1980s |

possible we have used the methodological and conceptual approaches that characterize the field. Table 1 summarizes our review.

### *Environmental Kuznets Curve for Materials*

The environmental Kuznets curve (EKC) is a widely used indicator of sustainable development (World Bank 1992).[3] The hypothesis underlying the EKC is that resource depletion and pollution increase in the initial stages of development but then tend to fall as incomes rise, producing an inverted U-shaped function. The argument is that environmental quality is a normal economic good, that is, people are willing and able to pay to consume more of it as incomes rise. Also implicit in the argument is the assumption that richer nations have the ability to pay for the investment in new technology that reduces pollution and degradation and that as economies mature, they produce a less energy- and materials-intensive mix of goods and services. Empirical analysis suggests that the relationship holds for some air pollutants (Seldon and Song 1994) and deforestation (Panayotou 1993). Some of the most optimistic assessments of future materials supply and demand assume that rising incomes will substantially decouple material use and economic growth (e.g., Brooks and Andrews 1974).

The EKC approach has been applied to material use by examining the relationship between IU and income in both time series and cross-sectional analyses (International Iron and Steel Institute 1972; Malenbaum 1978; Rogich 1993b; de Bruyn and Opschoor 1997; Jänicke et al. 1997). Most analyses find support for the EKC hypothesis. The standard explanation is based on assumptions about the materials demanded by an economy through successive stages of development. In the early stages of development when incomes are low, materials requirements also are low, particularly for metals and building materials because such economies are based largely on unmechanized agriculture. Industrialization drives an increase in materials demand to build basic infrastructure: roads, railways, bridges, factories, cities, pipelines, power grids, and so on. As development continues, the need for basic infrastructure declines and consumer demand shifts increasingly toward services, which are assumed to be less materials intensive. This transition slows and eventually reverses the increase in IU as a function of income.

Bernardini and Galli (1993) claim that the empirical research indicates not only the existence of an EKC for individual nations, but also that differences in the IU of an individual material among nations are explained by differences in their stage of economic development (figure 2). They postulate that nations complete development in successive periods at about the same level of per capita GDP and that the IU of a given material declines the later in time each country completes development.

A series of studies in the 1970s established the initial argument for a materials EKC (International Iron and Steel Institute 1972; Brooks and Andrews 1974; Radcliffe 1976; Malenbaum 1978). Malenbaum's (1978) analysis was particularly influential because it was prepared for the National Commission on Materials Policy (1973). Malenbaum analyzed the IU for 12 metals in the world economy from 1951 to 1975, breaking nations into major groups and comparing them with the United States. Malenbaum's index of IU was tons of metal per dollar of real GDP. Visual inspection of the data led him to conclude that IU among nations and metals shows a regular inverted U shape. Malenbaum concluded that the IU evidence demonstrates that "man's skill, knowledge, and aspirations" have effectively decoupled economic growth from growth in raw materials use. Malenbaum notes, however, that a complete analysis would account for materials embodied in imported finished goods.

Larson and colleagues (1986) and Williams and colleagues (1987) build on this early work in their analysis of materials use in the United States that culminates in their declaration that the "era of materials" is over. Larson and colleagues calculate the IU (weight per dollar GNP) for three "traditional" materials (steel, cement, paper) and four "modern" materials (aluminum, chlorine, ammonia, ethylene). Their visual inspection of the IU data as a function of per capita GNP reveals the inverse U shape, with the IU of even the "modern" materials now declining as a function of income.

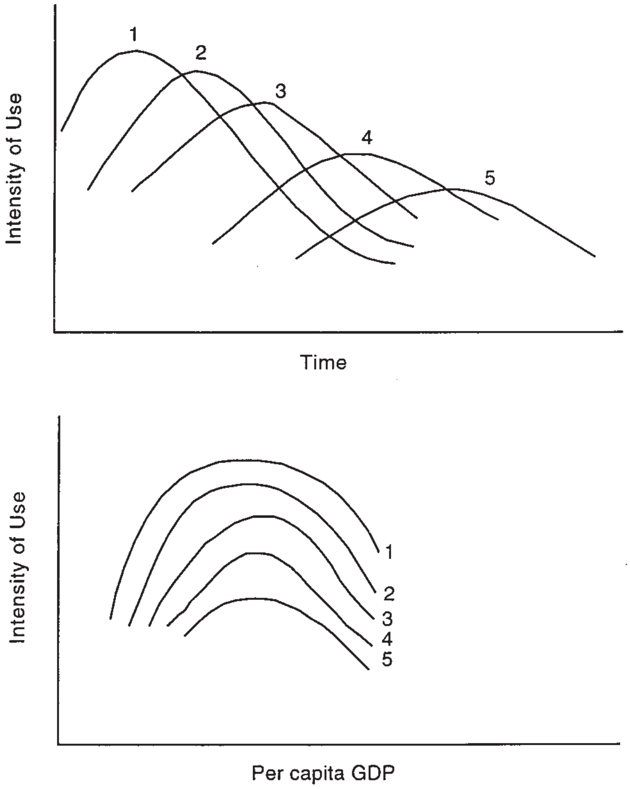

**Figure 2** Graphical representation of the materials environmental Kuznet curve as envisioned by Bernardini and Galli (1993). Nations 1–5 complete development in subsequent periods of time at around the same value of per capita GDP. The intensity of use of a given material declines the later in time each nation develops.

Using a database on total materials use in the United States developed by the Bureau of Mines, Rogich (1993b) uses regression analysis to compare the IU of paper, wood, metals, and plastics measured in weight and volume terms to per capita GNP from 1970 to 1989. It is difficult to interpret the results of Rogich's analysis. The regression line fit to the weight-based IU data has a negative slope, whereas that fit to the volume-based IU has a positive slope. However, no information is given to indicate whether the results meet any standard criteria for statistical significance. Rogich states that the low R-squared statistics are not "satisfactory." He goes on to state that if the results were significant, they would support the hypothesis that the United States is shifting its preferences to lower density materials but that "the consumption of materials is not declining as our standard of living improves."

Jänicke and colleagues (1989) develop an "index of structural environmental impacts" to measure the impact that structural economic change has had on the environment since the 1970s. They uses four indicators "whose direct and/or indirect environmental significance is indisputable": the consumption (weight) of steel, energy, cement, and the weight of freight transport by road and rail. Freight transport is intended to be a general indicator of the "volume aspect of production." They calculate per capita consumption of each indicator, then calculate the deviation from the mean for each, sum the deviations for all indicators, and then divide by four (the number of indicators). Thus, the four factors are weighted equally. Jänicke and colleagues (1989) use regression analysis to compare the index to per capita GDP in 31 industrial countries in 1970 and 1985. The regression line fit to the cross-sectional data in both years has a positive slope, although the slope for the 1985 data is less steep. No information is given to indicate whether the results meet any standard criteria for statistical significance. Jänicke and colleagues conclude that a substantial "delinking" occurred between material inputs and economic growth. However, they note that some eastern European nations showed increasing IU, whereas Japan and

Norway experienced overall economic growth that "canceled" the improvements in the material IU.

Jänicke and colleagues (1997) expanded their index to include more metals, some minerals, petroleum products, and agricultural chemicals. They compare this index to per capita GDP in 32 nations in 1970 and 1991. Visual inspection of the data led Jänicke and colleagues to conclude that IU generally falls with rising income for some materials (cement) but rises for others (paper). They conclude that a general decline in materials and pollution-intensive industries "has not so far become evident in the advanced industrial countries." In country-specific studies, Jänicke and colleagues find that data for the United States provide only "partial confirmation" of dematerialization, in this case made by a visual comparison of the absolute growth in GDP compared with absolute growth in the consumption of specific materials measured in tons. Steel, aluminum, and cement declined relative to GDP, whereas paper increased.

de Bruyn and Opschoor (1997) question the conclusions of Jänicke and colleagues (1989) based on the latter's use of just two observations in time (1970 and 1985) to draw conclusions about long-run and aggregate economic change. They also argue that Jänicke and colleagues do not distinguish between the effects of changes in materials intensity and changes in aggregate economic growth on the demand for materials. de Bruyn and Opschoor repeat Jänicke and colleagues' analysis with data from 1966 to 1990 for 19 nations. Their visual inspection of the data led them to conclude that most nations did exhibit delinking from 1966 to 1984 but that some developed nations "relinked" in the late 1980s (i.e., exhibited increasing energy and materials intensity as a function of GDP). The result is an "N-shape" path rather than the inverted U shape.

Another version of the material EKC compares the generation of material waste with income. The most common application describes dematerialization as the decreasing carbon intensity of energy use as a function of income. Carbon intensity is the quantity of carbon released (weight) per dollar of output. Grübler and Fujii (1991) plot carbon intensity (kg/GDP) against income (per capita GDP) for the U.S. economy from 1800 to 1988 and find a nearly threefold decline. Grübler (1994a) plots industrial carbon intensity (kilograms per dollar of industrial value added) as a function of per capita industrial value added for six nations in various stages of development. In most nations, carbon intensity falls with rising per capita industrial value added, with most intercountry differences explained by different degrees of industrialization and hence differences in the technology and structure of industry.

### *Material Use and Long Waves in Technology and the Economy*

Another body of work ties the pattern of material use over time to regular patterns of technological development. The principal differences between this work and the materials EKC work is that time replaces income as the independent variable, and specific functional forms are used to describe the pattern of technical change and material substitution. Many of the presumed driving forces remain the same (i.e., technical change, materials substitution, changes in final demand).

Long wave theory in economics postulates that technologies proceed through a life cycle of early development, rapid diffusion and adoption, and ultimately saturation and senescence (Kuznets 1930; Kondriatiev 1935; Schumpeter 1939; Ayres 1989b). The forces that determine the speed and extent of technology diffusion change over time; they include performance, cost, fashion, and familiarity (Grübler 1996). The assumption is that the variations in timing and driving forces at the micro level often lead to smooth orderly behavior at the macro level. Technology diffusion often is assumed to follow an S-shaped curve such as a logistic function (Fisher and Pry 1971). In this case, the diffusion or growth of a technology ($Z$) is defined as

$$Z_t = \frac{k}{\left(1 + e^{\left(-b\left(t - t_m\right)\right)}\right)} \tag{3}$$

where the slope parameter $b$ defines the diffusion rate of $Z$, $k$ is the upper asymptote or saturation level, and $t_m$ is the inflection point. Logistic substitution models describe the rate at which a technology captures market share.

The logistic substitution model has been used to model the growth of major transportation and communication infrastructures in the United States (Grübler 1990, 1996), the substitution of emissions controls in the U.S. vehicle fleet (Nakicenovic 1986), primary energy substitution in the United States (Nakicenovic 1990), and other phenomena. These concepts have been applied to long-run patterns of material use. Fisher and Pry (1971) use the logistic substitution model to describe the timing of 17 specific cases of materials substitution in the United States, including synthetic for natural rubber, open-hearth for Bessemer steel, and synthetic detergents for soaps.

Although not using the explicit substitution model defined in equation (3), other analysts have proposed long-run models of technical change to describe historic patterns of materials use. Rostow (1975) and Volland (1987) proposed theories of long-run patterns in energy and raw materials use based on changes in the profitability of production. Supply constraints based on short-run, market-driven scarcities (Rostow) or long-run scarcities due to depletion (Volland) cause commodity prices to rise. In turn, rising commodity prices stimulate the development of new cheaper technologies based on more abundant materials that ultimately replace the old technologies. Volland (1987) notes that the new technologies not only are based on more plentiful supplies, they also may be efficient users of existing materials, less resource intensive, or based on renewable materials.

Taking a slightly different perspective on long-run technology development, Grübler (1994b) describes industrialization as an historical succession of periods of "pervasive adoption of clusters of technological and organizational innovations." Each cluster is a mixture of "leading" sectors driving growth and older sectors, and is characterized by specific combinations of energy and natural resources. Grübler argues that industry has a "built-in" incentive structure to minimize energy and material inputs, primarily driven by "economics and continuous technological change." He then asserts that industry automatically "moves in the right direction" by minimizing material inputs per unit output and by reducing the environmental impact of energy and material use. Grübler cites the decline in the energy/GDP ratio and the carbon intensity of many industrial nations as evidence for this argument.

Some analysts postulate that the pattern of the IU of metals (Tilton 1990) and materials in general (Larson et al. 1986, Williams et al. 1987) show a long inverted U shape as a function of time, similar to the materials EKC. When materials are introduced, they go through a period of rising IU as developing technology permits their substitution for other materials in existing products and in entirely new applications made possible by their special properties. In this phase, expanding use offsets the downward pressure on IU by resource-saving technology (Tilton 1990). In the second phase of the cycle, saturation of end uses for the material causes increasing competition from substitutes, and the increase in IU slows, levels off, and begins to decline. In the final phase, more "sophisticated" products are made, and the ratio of value added to material use increases. Resource-saving technical change accelerates this process. In this phase, the GDP intensity of use peaks and declines, whereas the per capita IU may still increase. In the final phase of the cycle, market saturation and substitution effects dominate, causing IU to fall sharply; per capita consumption levels off and also may decline.

Larson and colleagues (1986) and Williams and colleagues (1987) apply this approach to the IU of metals and secondary materials in the United States. They defined IU in terms of weight per dollar GNP or per capita. Williams and colleagues' (1987) visual inspection of the IU for seven secondary materials and ten metals in the United States led them to conclude that a substantial decoupling occurred. They attribute the "maturing of basic materials" in the United States to improvements in the efficiency of materials use, substitution of cheaper materials or materials with more desirable properties of traditional materials, saturation of bulk markets for materials, and shifts in consumer preferences at high income levels to less materials-intensive goods and services.

Labys and Waddell (1989) use the theories of long wave economic cycles and the S-shaped function of technology diffusion to reject the standard interpretation of dematerialization. Instead of a once and for all structural change as implied by dematerialization, Labys and Waddell argue that minerals demand experiences phases in which older lower quality materials linked to mature industries undergo periodic replacement by higher quality or technologically more appropriate materials. They call this process transmaterialization. According to this theory, IU for a single material will show a long-run inverted U-shaped path as a function of time. For the economy as a whole, the dynamics of transmaterialization produce many overlapping inverted U-shaped paths. Labys and Waddell construct five broad materials groups and show that their IU (as measured by weight per GDP) show inverted U shapes from 1930 to 1985. Their visual analysis of the data led them to conclude that timing of the peak IU for the groups indicates that "replacement has occurred at regular intervals." Fortis (1994) presents similar data and arguments.

Roberts (1992) observes that the dynamics of the material composition of products, ($X_i/Y$) in equation (1), are the result of short-run improvements in product design and efficiency improvements and long-run improvements from major technical changes that redesign products and manufacturing plants. Roberts models the short-run factors with learning curves that assume that the material composition of product declines as an exponential function of cumulative production. The longer run diffusion of new technologies is modeled by a logistic function similar to that in equation (3). Roberts applies this approach to explain the dynamics of the substitution of aluminum for steel in the U.S. beer container market from 1950 to 1986. Roberts (1996) extends his analysis to account for the determinants of apparent metal consumption, including metal exports and imports.

### Material Decomposition Analysis

Decomposition analysis is based on the quantification of an accounting identity such as that defined in equations (1) or (2) to identify the economic, demographic, or technological forces affecting IU.

Considine (1991) begins with the accounting identity for IU defined in equation (2) and breaks down the material composition term as follows:

$$\left(\frac{X_i}{Y}\right)=\left(\frac{X_i}{Q_m}\right)\left(\frac{Q_m}{Y}\right) \tag{4}$$

where $Q_m$ is the Divisia index of aggregate material consumption. The first term on the right-hand side of equation (4) reflects intermaterial substitution, whereas the second term results from interfactor substitution (i.e., substitution among capital, labor, energy, and materials). Considine uses this approach to analyze the IU for steel, copper, aluminum, plastic use in the manufacture of sheet, strip, pipe, and wire products in the United States from 1960 to 1985. The aggregate materials IU ($X_i/Y$) showed no overall trend, whereas the IU for steel and aluminum declined. At the same time, the IU for plastics and copper increased. Considine uses equations (1) and (3) to measure the three sources of change in the IU for steel: the two substitution effects and the product composition of output. About 80% in the decline in the IU for steel is due to intermaterial substitution ($X/Q_m$), 4% is due to interfactor substitution ($Q_m/Y$), and 16% is due to product compositional shifts ($Y/GNP$).

Roberts (1988) uses equation (1) to decompose the causes of the significant slowdown in the demand for eight major metals in the world economy after 1974. The results suggest that the most important factor behind the slower consumption of metals was slower growth in GDP, followed by a decline in the product composition of income, the latter of which Roberts attributes to a shift away from metal-intensive products. The material composition of product declined for all metals over the entire period (1960–1984), except for aluminum, suggesting that substitutions and technical changes driving reductions for the seven metals by themselves could not explain the sudden slackening in demand after 1974.

Roberts (1990) uses a variation of equation (1) to forecast steel consumption in the United States. The apparent consumption ($X_i$) of a metal such as steel is defined by the identity

$$X_i=\left(\frac{X_i}{Y}\right)\left(\frac{Y}{GNP}\right)(GNP)+\left(\frac{X_i}{Y}\right)(N_i) \tag{5}$$

where $N_i$ is the quantity of material $i$ in net exports and the other variables are those defined in equation (1). Roberts uses regression analysis to forecast the material composition of product as a negative exponential function of time, which is assumed to capture the effects of technical change. The product composition of income and net exports are forecast as a function of per capita GNP, time, and exchange rates. These forecasts are combined to produce a forecast of steel consumption in 2000, which is significantly lower than the U.S. Bureau of Mines' forecast.

Taking a somewhat different approach, Waggoner and colleagues (1996) use the "IPAT" equation (Commoner 1972) to decompose the factors responsible for changes in the consumption of paper and lumber in the United States from 1904 to 1990. Consumption (in tons) is defined by

$$\text{Consumption} = (\text{Population})\left(\frac{\text{GNP}}{\text{Population}}\right)\left(\frac{\text{Consumption}}{\text{GNP}}\right). \quad (6)$$

Waggoner and colleagues' decomposition analysis reveals that total paper consumption grew at an average rate of 4% per year over this period, driven by increases in paper use per GNP (0.9% per year), per capita income (1.8% per year), and population (1.3% per year). In the case of lumber, material intensity fell nearly 2.8% per year, nearly offsetting the effects of rising population and affluence. Waggoner and colleagues conclude that the decline in the IU for lumber is one reason for the expansion of forest area in the United States that began in the 1920s.

Wernick and colleagues (1997) use a version of the IPAT model to assess the factors responsible for changes in the demand for forest area used to supply forest products in the United States from 1900 to 1993. Their model is

$$\text{Forest Affected} = \left(\frac{\text{Forest Affected}}{\text{Wood}}\right)\left(\frac{\text{Wood}}{\text{Paper}}\right)\cdot \left(\frac{\text{Paper}}{\text{GDP}}\right)\left(\frac{\text{GDP}}{\text{Person}}\right)(\text{Population}). \quad (7)$$

The third term on the right-hand side of equation (5) is the IU of industrial products, measured in cubic meters per dollar of GDP. Wernick and colleagues find that the IU of total wood product declined at an average annual rate of 2.5% over the period. They conclude that the decline in IU was a principal reason why the use of timber products only doubled from their 1900 levels, whereas GDP increased 16-fold.

### *Statistical Analysis of Intensity of Use*

Ross and Purcell (1981) analyze the trends in the IU of the U.S. pulp and paper industry. Their data show that the IU (weight per dollar GDP) generally increased from 1950 to 1979. Without specifying a model and presenting statistical results, Ross and Purcell report that the results of a regression analysis show that IU for all paper products increased at an average annual rate of 0.2% over the entire period, although from 1969 to 1979 the IU fell by 1.0% per year. Focusing on the 1960–1979 period, Ross and Purcell find that the IU for paper in shipping containers increases sharply in the 1960s before leveling off, a trend they attribute to the saturation in new uses of those containers. The IU of paper for newsprint drops sharply from 1960 to 1979 due to the development of paper with lower weight per unit area and competition with electronic media. The IU of paper packaging and boxboard production declined from 1960 to 1979 due to substitution by plastics.

Humphreys (1994) and Moore and colleagues (1996) analyze the IU of nonferrous metals and construction materials in the United Kingdom and United States, respectively, from 1960 to 1992. Intensity of use is measured by the dollar value of material consumption divided by GDP. Humphreys found that IU for metals declines, whereas that for construction materials rises, a trend he attributed to the rise of the service sector and a decline of the manufacturing sector in the United Kingdom. Moore and colleagues find the IU declined for both sectors, although their regression analysis did not support Humphreys' argument that such changes could be explained by the changes in the importance of the service and manufacturing sectors in the United States. Moore and colleagues speculate that other forces are more important determinants of IU, such as resource-saving new technology, materials substitution, and intrasectoral shifts within the manufacturing sector.

Labson and Crompton (1993) and Labson (1995) suggest that previous work on IU embodies a fundamental problem: Ascribing a trend to IU from visual inspection of time series data (e.g., Larson et al. 1986) or running a regression of IU or material consumption on income or time implies that a stationary relationship exists between material use and income and/or time. A series is weakly or covariance stationary if its mean and autocovariances do not depend on the date. However, none of the reviewed studies ever test that assumption, raising questions about the significance or reliability of conclusions drawn from that research.

Labson and Crompton (1993) develop a cointegration model of the relation between income and the consumption of steel, copper, lead, zinc, and tin in the United States, Japan, the United Kingdom, and the countries comprising the Organization for Economic Cooperation and Development (OECD)[4] in the post–World War II period. They also perform cointegration tests for IU, defined as weight per dollar GDP, for the same regions and time periods. They find little evidence for a long-run equilibrium relationship between income and metal consumption, and that IU is best described as a stochastic trend. Labson and Crompton (1993) conclude that whereas IU may be a helpful measure of describing the history of metals demand, it cannot be used for purposes of inference without explicit consideration of its stochastic nature and that "any apparent trends are illusory, and should be treated as such until proven otherwise."

In a subsequent analysis, Labson (1995) applies cointegration techniques to the analysis of the IU for six metals in the United States and OECD from 1946 to 1992. Labson again emphasizes that previous analysis of IU based on trend analysis implicitly assumes stationarity about a deterministic time trend. A deterministic time trend is one with no stochastic behavior. Labson tests for a unit root in IU with a 1973 break point as suggested previously by Tilton (1985, 1990) and others. Labson finds that OECD steel, tin, and zinc demand does follow in "lockstep" with economic activity, implying that technical innovations are not "of such a deep nature as to impart a permanent influence on IU over reasonably interesting time horizons."

### *Input-Output Analysis*

Input-output analysis can be used to test hypotheses about economic and technological forces shaping materials use, such as changes in consumption patterns, import mix, input substitution, and improvements in material use efficiency. Structural decomposition analysis can measure the relative contribution of those factors to changes in IU. Although input-output analysis traditionally is based on monetary flows, the hybrid units method supplements monetary data with energy and material flows in physical units. This approach has been used extensively to study changes in the energy intensity of economic activity (e.g., Hannon 1982) and more recently to study material waste flows and recycling (Duchin 1994, Duchin and Lange, 1994). Ayres (1978) provides a good overview of some of the technical issues surrounding the application of input-output analysis to materials, with empirical examples from the U.S. economy.

Carter (1966) was the first to use input-output analysis to draw conclusions about changes in material use. Carter compared input-output tables for 1947 and 1958 and examined the impacts of structural change on industrial specialization and economic efficiency, including material input requirements. Carter disaggregated materials into nine categories, covering all the major nonenergy inputs to the economy. She found an overall decline in the quantity of materials and semifinished goods used to produce the nation's economic output from 1947 to 1958. Carter also found a significant diversification of material inputs, reflecting an increase in the "keenly competitive refinement" in the qualities of materials and product design driven by changes in final demand.

Leontief and colleagues (1983) develop an input-output model of the U.S. and world economy to forecast changes in the use of nonfuel minerals from 1972 to 2000. Their measure of IU is the physical quantity of material used per dollar output of the consuming sector. Their analysis covered 18 primary metals, 13 secondary (recycled) metals, and 8 nonmetals. For the U.S. economy as a whole, the authors forecast a decline in the IU for 14 of 18 metals; the IU of all the nonmetals was forecast to increase.

Duchin and Lange (1994) develop a 16-region input-output model of the global economy and use it to analyze different scenarios of how future growth and technical change will affect energy and material use and waste generation.

They analyze the processing and fabrication of six major metals, and material use in the construction cement, pulp and paper, and chemical industries. Their index of material intensity is the input coefficient: the value of a material or material service delivered per dollar of output of a particular industry that uses that material. Duchin and Lange found a decline in the input coefficient for overall metal use in the 1980s in industrial nations, although the input coefficients of zinc and aluminum increased. They forecast further declines in most metal input coefficients for 1990–2020, although the rate of decline will be slower than in the 1980s.

### *Dynamic Models*

Dynamic computer-based simulation models have addressed the interconnections among depletion, technical change, substitution, and market dynamics that affect material use. Most studies concentrate on a small set of products. Ince (1994) uses linear programming to model and forecast fiber supply, changes in technology and capacity utilization, and market dynamics in the U.S. and Canadian paper industry. The model includes a forest sector component and process-level data of various manufacturing processes and provides a high degree of disaggregation by product, region, and stage of paper production. Model results indicate that U.S. paper and board consumption will increase by more than 70% from 1986 to 2040, whereas per capita consumption will increase by roughly one-third. Projected energy and material efficiency improvements combined with increases in wastepaper utilization rates that are expected to occur will not be sufficient to decrease industrial material and energy consumption.

Concentrating on issues of technological change and wastepaper utilization in U.S. pulp and paper production, Ruth and Harrington (1997a, b) confirm Ince's results. They use simulation models with information from engineering studies and time series analysis to investigate likely future material and energy use profiles by the industry. The results point to a significant potential for biomass-based energy, especially in the form of waste-to-energy conversions, to substitute for purchased fossil fuels. Subsequent analysis (Ruth and Davidsdottir 1997) suggests that this potential will be more aggressively explored if climate change policies raise fossil fuel prices. Increased waste-to-energy conversion, combined with strong demand for the industry's products, will result in greater demand for virgin fiber sources.

Ruth and Dell'Anno (1997) use a similar approach in their analysis of the U.S. glass industry. Disaggregating glass manufacturing into four subsectors (container glass, flat glass, fiberglass insulation, and textile fiberglass), three main production stages, recycling, and raw material extraction, they find that by the first quarter of the next century, technological improvements and expansion of recycling will reach technologically determined limits. After this point, material and energy consumption are likely to follow in step with changes in demand. These results hold over a wide range of scenarios about future trends in technology and product demand.

The emphasis of dynamic models so far has been less on hypothesis testing than on an investigation of the implications that various time-lagged and nonlinear feedback mechanisms may have for energy use and emissions through time. Technology change, recycling, and changes in demand for finished products may reduce raw material requirements by the economy. Increases in the scarcity of raw materials may counteract the declines in energy demand and emissions that come from reduced material requirements (Nieuwlaar and van Gool 1990; Cleveland and Ruth 1996). Ruth (1998) assesses the net effects that dematerialization would have on energy use and $CO_2$ emissions from copper, lead, zinc, aluminum, and iron and steel production in the United States. He finds that if historic trends continue, total carbon emissions from the extraction and refining of those five metals would decline more rapidly than energy use over the next 30 years by those five industries. These results are consistent with the notion of a decarbonizing economy.

### *Analyses of Aggregate National Material Use*

An important and visible body of work compares the use of specific materials and material aggregates to national economic output, usually

GDP or GNP. These analyses thus attempt to say something about the overall efficiency of material use. Spencer (1980) produced what proved to be the last in a series of updates (Spencer and Wardwell 1954; Spencer 1963, 1969, 1972) of the seminal work by the President's Materials Policy Commission (1952) on raw material use in the United States. Spencer reports the real (i.e., inflation-adjusted) dollar value of all raw material consumption (materials, energy, and food) in the United States from 1900 to 1977. Per capita consumption of all materials increased from $372 to $454 (constant 1972 dollars). Spencer's index of IU was the ratio of GNP to the value of material use, which increased by more than a factor of three over the period, indicating to Spencer that we "have made great strides in making raw materials go further" (p. 10).

Rogich (1996b) reported the results of research by the U.S. Bureau of Mines that is based on a comprehensive database on materials consumption in the United States from 1900 to 1990 for dozens of individual materials in five major groups: agriculture, forestry, nonrenewable organics, metals, and minerals (Rogich 1993a, 1993b, 1996a). He defined intensity of use as either weight consumed per dollar of GDP or weight consumed per capita. Rogich found an increase in the absolute consumption of materials from 142 million metric tons in 1900 to 2.5 billion metric tons in 1989. In terms of per capita consumption, some material groups show declining IUs (most metals and minerals), some display a relatively constant IU (forest products), whereas others show increasing IU (nonrenewable organics). Rogich (1993a) concludes that "any significant decrease in material flow per capita is not apparent." However, Rogich (1996b) finds that per unit of GNP, overall materials IU declined from 1970 to 1990, a trend he attributed to the fact that "services are contributing a growing share to our GNP." Rogich (1996b) also presents materials consumption on a volumetric basis. Measured in this way, plastics consumption exceeds that of metals, the decline in IU for GNP is smaller, and the per capita IU actually increased in the 1980s. Rogich (1993b) hypothesizes that this increase is due to an increase in the velocity of goods turnover.

Analysts with the Program on the Human Environment at Rockefeller University have developed a database on the IU of some important materials in the United States since 1900 (Wernick 1994; Wernick and Ausubel 1995; Wernick et al. 1996; Ausubel 1996). The IU (weight per dollar GNP) for plastic, aluminum, potash, and phosphorous increased from 1900 to 1990, whereas IU for timber, copper, steel, and lead declined. For the entire U.S. economy Wernick and colleagues (1996) found that IU as measured by weight per dollar GNP declined by one-third from 1970 to 1990. On the measurement issue, Wernick and colleagues (1996) argue that material consumption cannot be satisfactorily reduced to a single elementary indicator because materials possess unique properties that provide value, define use, and have environmental consequences. They observe that newly exploited materials such as gallium, the platinum-based group, and vanadium increasingly are used in very small quantities for electronic and other "designer materials." Measuring their contribution in mass terms may understate their economic importance and environmental implications. Wernick and colleagues also report that measured in volume terms, per capita use of materials has increased along with economic growth. Plastics account for much of the growth in volume. Wernick and colleagues conclude that individual items may be getting lighter, but the economy as a whole is physically expanding. Because of these issues, Wernick and colleagues argue for an "ensemble" of measures under the rubric of dematerialization, although they utilize only their weight-based index.

Wernick (1994) discusses the role of secondary materials recycling in the dematerialization of specific products and the U.S. economy as a whole. Noting the decline in the reliance on traditional bulk materials used principally to provide structure, Wernick observes that a more diverse menu of materials is used for "smarter, more intrinsic functions." The diversification of materials, their composition, and their end use has made secondary recovery increasingly complex. In electric arc furnace steel production, for example, trace amounts of zinc, copper, tin, and other impurities pose significant challenges to secondary recovery.

Analysts at the Wuppertal Institute have developed the concept of "material input per unit of service" (MIPS) to measure material resource productivity (Schmidt-Bleek 1994; Bringezu 1997; Hinterberger et al. 1997). MIPS includes two types of material flows. Direct materials inputs are the natural resource commodities that enter the economy for further processing (i.e., the usual categories of agricultural, metal, mineral, wood, and petrochemical materials). "Hidden" material flows, or "ecological rucksacks," are materials removed from the environment along with the desired material and the material moved or disturbed in resource extraction or in building and maintaining infrastructure. Examples include waste rock from ore separation, plant biomass harvested in logging that later is separated from the desired forest product, overburden produced from a mining operation, soil erosion in agriculture, and dredging of waterways. MIPS is intended to provide an indicator of the potential for overall environmental impact from economic activity (Schmidt-Bleek 1994; Bringezu 1997).

Bringezu (1997) applies the MIPS methodology to the German economy, defining its material productivity as the ratio of GDP to the direct and hidden inputs of materials (the inverse of IU). Materials are measured in tons. He finds that material productivity increased by about 40% from 1975 to 1987 but then declined somewhat thereafter, a temporary trend Bringezu attributes to the inheritance of relatively inefficient technologies in the German reunification process. Bringezu concludes that the results suggest a possible decoupling of material input from economic performance.

Adriaanse and colleagues (1997) use a similar approach in their comparative analysis of materials use in Germany, the Netherlands, Japan, and the United States from 1975 to 1994. Adriaanse and colleagues calculate direct material inputs and the hidden flows for six categories of materials: fossil fuels, metals and industrial minerals, construction materials, renewable resources, infrastructure creation and maintenance, and soil erosion. They calculate IU as the ratio of direct and indirect material inputs, measured in tons, per dollar of GDP. The IU of direct and indirect materials suggests a "modest decoupling" over the period, although the ratio rises in Germany and the Netherlands toward the end of the period. The intensity of use for direct materials shows a modest decline, followed by a leveling in the last 10 years of the period, suggesting that "direct inputs of natural resources are now growing in parallel with economic growth" (p. 14).

## Measurement of Aggregate Material Use

Aggregation is one of the most vexing problems in the analysis of materials use. Analysis of the relation between material use as a whole and economic activity requires the analyst to aggregate different materials, a procedure usually accomplished by summing their mass or weight. Equation (8) illustrates this approach:

$$M_t = \sum_{i=1}^{N} M_{it} \tag{8}$$

where M represents the weight or mass of material $i$ ($N$ types) at time $t$. As table 1 indicates, the overwhelming majority of studies aggregate materials by weight. There are obvious reasons for this. First, and probably most important, agencies such as the U.S. Bureau of Mines collect and report data on materials use in terms of weight, so it is easy to assemble databases in which material measurement and aggregation are based on weight. Second, weight is easily and uncontroversially measured. Third, accounting for materials in mass terms allows us to "balance the books" in life-cycle analyses of products or in analyses of the industrial metabolism of specific materials (Stigliani and Anderberg 1994). Ensuring that the law of conservation of matter is met by tracking the mass of materials is a foundation of industrial ecology.

In most analyses of materials IU, analysts aggregate materials by weight with little or no discussion of its strengths, weaknesses, or implications for interpreting its economic or environmental significance. Larson and colleagues (1986) state they use weight instead of dollars to "give a sharper picture of the changing role of materials" without elaboration of how or why that is the case. Others offer more substantive justifications for weight-based indices. Williams and colleagues (1987) argue that economic output such as sales or value added often are not disaggregated enough to reveal the shifts to new higher value products and that if one is interested in industrial energy demand, it is better to track kilograms because energy requirements of industrial production are closely tied to physical measures of materials.

Radetzki and Tilton (1990) defend the use of weight to measure metal consumption on a number of grounds. First, assembling a time series of quality-weighted consumption across a number of countries is practically impossible. Second, new technology can enhance quality without increasing the value of metal production. The introduction of multiplexing in the 1960s increased the number of two-way voice conversations that could be carried over a single twisted pair of copper wires. Radetzki and Tilton argue that this may have caused the number of tons or the value of copper wire to decrease in telecommunications, whereas the quality of service obviously rose. Third, the variety of attributes metals provide—strength, appearance, corrosion resistance, heat conductivity, and so on—are too numerous to be properly reflected in a single quality-adjusted metric. Finally, forces unrelated to quality, such as cartels, regulation, and labor and capital costs, can affect the price or value of metals.

Cochran (1988) and Rogich (1996b) argue that volume may be better than weight because in many instances users choose technically competitive materials based on lowest cost per unit volume, not weight. In fact, from an engineering perspective, weight in most applications is a deleterious property. Volume is the exact basis of substitution only when the applications are simply filling space as in casting, molding, or sheets of fixed gauge, but Cochran argues it is a more reasonable proxy than weight. Analyzing the long-run path of prices and consumption of nine new and old basic materials, Cochran argues that most long-run shifts in different basic materials in the United States can be explained in terms of users choosing materials based on the lowest price per unit volume among technically suited materials. Rogich (1996b) observes that by far the largest category of material use in weight terms is construction materials. Because much of the basic infrastructure of the U.S. economy is already in place (roads, bridges, buildings, etc.), it is not surprising that the weight-based IU for the economy has declined. Similarly, Cochran questions conventional wisdom of the passing of the “era of materials” and instead argues that new lower density materials such as plastics and aluminum have become cheaper per unit volume, and as a result they replace older materials such as pig iron and copper in markets where the new materials are technically qualified.

Despite their widespread use, aggregation by weight or volume embodies a serious flaw: It ignores material quality. In this context, *material quality is the marginal amount of economic output generated per mass unit of material input.* How does one measure material quality? Modification of the standard method of material aggregation to account for material quality requires a system that weights the mass of each material by its relative economic usefulness. Such an approach defines a new aggregate material, M*, as the weighted sum of individual material types:

$$\mathrm{M}_t^* = \sum_{i=1}^{N} \lambda_{it} \mathrm{M}_{it} \qquad (9)$$

where the λ's are quality factors that may vary among materials and over time for individual materials. The next and more difficult step is the technique used to calculate λ. We discuss several alternatives below.

### *Economic Approaches to Material Quality*

Aggregation has received substantial attention from economists because it is essential for the construction of production and consumption functions and for the reduction of the number of parameters in econometric models. Measurement of productivity, for example, requires a method to aggregate the different goods produced and the different factors of production that have diverse and distinct qualities. For example, the post–World War II shift in Western economies toward a more educated work force and from nonresidential structures to producers' durable equipment requires adjustments to methods used to measure labor hours and capital inputs (Jorgensen and Griliches 1967). Many

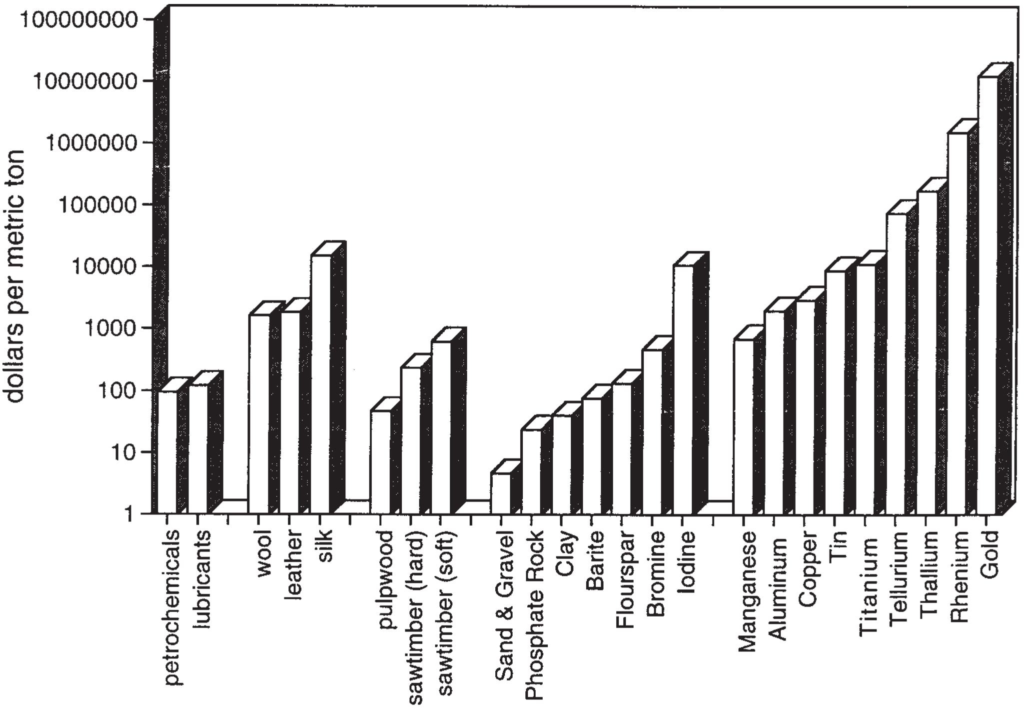

**Figure 3** Unit prices ($/metric ton) for various materials in the United States, mid-1990s.

indices are possible, so economists have focused on the implicit assumptions made by the choice of an index in regards to returns to scale, substitutability, and other factors.

From an economic perspective, the value of any input—capital, labor, energy, or material—is determined by its marginal product, which is the marginal increase in the quantity of a good or service produced by the use of one additional unit of the input. The marginal product of a material is determined in part by a complex set of attributes unique to that material. For example, metals vary by their impact resistance, heat resistance, corrosion resistance, stiffness, space maintenance, conductivity, strength, ductility, and other properties, all of which combine with other technological and economic factors to determine why users choose one metal over another. All other classes of materials have an analogous set of attributes that vary by individual material.

In addition to attributes of the material such as density or weight, marginal product also depends on the state of technology, the level of other inputs, and other factors. According to neoclassical economic theory, the price per ton of material should equal its marginal product and therefore represent its economic usefulness. In theory, the market price of a material reflects the myriad factors that determine the economic usefulness of a material from the perspective of the end user. Consistent with this perspective, the price per ton varies substantially among materials (figure 3). The different prices demonstrate that end users are concerned with attributes other than weight.

Do market signals (i.e., prices) accurately reflect the marginal product of inputs? Materials have not been studied in this regard, but Kaufmann (1994) investigates this question in an empirical analysis of the relation between relative marginal product and price in U.S. energy markets. To do so, he estimates a reduced form of a production function that represents how the fraction of total energy use from coal, oil, natural gas, and primary electricity (electricity from hydro and nuclear sources) affects the quantity of energy required to produce a given level of output. The partial derivatives of the production function with respect to each of the fuels gives the marginal product of individual fuels, where marginal product is defined as the change in economic output given a change in the use of a heat unit of an individual fuel. The equations are used to calculate the marginal product for each fuel type for each year between 1955 and 1992. The time series for marginal product are compared among fuels, and these ratios are related to relative prices using a partial adjustment model. The results indicate that there is a long-run relation between relative marginal product and relative price although it takes several years for the marginal products of fuels to adjust to changes in their relative prices.

### *Price-Based Aggregation*

If marginal product is related to its price, material quality can be measured by using the price of materials to weight their mass units. The simplest approach defines the weighting factor (λ's) in equation (9) as

$$\lambda_{it} = \frac{P_{it}}{P_{1t}} \tag{10}$$

where $P_{it}$ is the price per ton of material. In this case, the price of each material is measured relative to the price of material type 1.

The quality index in equation (10) embodies the restrictive assumption that materials are perfect substitutes, and it is sensitive to the choice of numerator. Because materials are not perfect substitutes, a rise in the price of one material relative to output will not be matched by equal changes in the prices of the other materials relative to output.

The ideal index for aggregation is one that has the most realistic assumptions about substitution among materials and about the mechanisms by which users choose materials. The index that achieves this with the least restrictive assumptions is the Divisia index for aggregate prices and quantities (Diewert 1976). The discrete approximation to the continuous Divisia index of materials (M*) is

$$ln\,M^*_t - ln\,M^*_{t-1} = \sum_{i=1}^{n}\left(\left(\frac{P_{it}M_{it}}{2\sum_{i=1}^{n}P_{it}M_{it}} + \frac{P_{it-1}M_{it-1}}{2\sum_{i=1}^{n}P_{it-1}M_{it-1}}\right)\left(ln\,M_{it} - ln\,M_{it-1}\right)\right) \tag{11}$$

where *P* are the prices of the *n* materials and M is the quantity (weight) of each material. Note that prices enter the Divisia index via cost or expenditure shares. The Divisia index permits variable substitution among material types without imposing a priori restrictions on the degree of substitution (Diewert 1976).

In justifying his use of the Divisia index in his analysis of steel consumption, Considine (1990, 1991) observes that total steel consumption includes sheet, strip, wire, tube, bars, and many other products. In addition, there are three different grades of steel within each product class: carbon, alloy, and stainless. Each steel product has a different unit price that largely reflects their physical properties. Simply adding the tonnage for each class ignores these quality differences and implies that the components are perfect substitutes, which obviously is not the case. McSweeny and Hirosako (1991) make a similar argument when they state that steel users have a demand for usable strength—they do not have a direct demand for tons of steel. As Considine observes, the Divisia index of material use allows a consistent comparison of material use with GNP because it embodies the multidimensional attributes of materials, just as GNP embodies the multidimensional attributes of the goods and services produced by an economy.

Cleveland and colleagues (1998) review case studies that apply economic approaches such as Divisia aggregation to energy use and its relation to economic growth. For example, Stern's econometric analysis (1993) finds a significant causal relationship between energy use and GDP in the United States when energy quality is accounted for. Kaufmann (1992) finds that much of the variation in the aggregate energy/GDP ratio on the United States is explained by changes in the quality of fuel mix. These results indicate that accounting for differences in energy quality is needed to understand the underlying long-run relation between energy use and economic activity.

Aggregation using price has its shortcomings. Lau (1982) suggests that prices provide a reasonable method of aggregation if the aggregate cost function is homothetically separable in the raw material input prices. This means that the elasticity of substitution between different fuels (i.e., how easily one fuel can be substituted for another) is not a function of the quantities of nonfuel inputs used. This may be an unrealistic assumption in some cases. Also, the Divisia index assumes that the substitution possibilities among all fuel types and output are equal.

Another limit on the use of prices is that they generally do not exist for wastes. Thus, an economic index of waste flows is impossible to construct.

It is well known that material and energy prices do not reflect their full social cost due to a number of market imperfections. This is particularly true for the environmental impact caused by their extraction and use. Externalities thus bias prices, and hence an index based on prices, to an unknown extent. But this problem also characterizes physical approaches to aggregation based on weight, volume, or exergy. The relative weight of plutonium and sand consumption, for example, obviously has little if anything to do with their relative potential for environmental impact.

### *Aggregation Based on Exergy*

Ayres and colleagues (1996) and Ayres and Martiñas (1995) propose a system of aggregating energy and materials based on exergy. Exergy measures the (physically) useful work obtainable from an energy or material and is based on the chemical energy embodied in the material or energy based on its physical organization relative to a reference state. The physical units for exergy are the same as for energy or heat, namely kilocalories, joules, BTUs, and so on. For fossil fuels, exergy is nearly equivalent to the standard heat of combustion; for other forms of energy, specific calculations are needed that depend on the details of the assumed conversion process. For materials, exergy is defined jointly for a material and the reference state with which it must ultimately reach thermodynamic equilibrium (Ayres et al. 1996). Thus, exergy measures the degree to which a material is organized relative to a random assemblage of material found at an average abundance in the earth's crust, an average concentration of seawater or of gases in the atmosphere. The higher the degree of concentration, the higher the exergy content.

Ayres argues that exergy has a number of useful attributes for aggregating heterogeneous energy and materials. Exergy is a property of all energy and materials and in principle can be calculated from information in handbooks of chemistry and physics (e.g., Linde 1991–1992) and secondary studies (e.g., Szargut et al. 1988). Thus, exergy can be used to measure and aggregate natural resource inputs as well as wastes. For these reasons, Ayres argues that exergy forms the basis for a comprehensive resource accounting framework that could "provide policy-makers with a valuable set of indicators." One such indicator is a general measure of "technical efficiency," the efficiency with which "raw" exergy from animals or inanimate sources is converted into final services. A low exergy efficiency implies room for improvement in the efficiency of converting energy and materials into goods and services. Similarly, the ratio of exergy embodied in material wastes to exergy embodied in resource inputs is the "most general measure of pollution" (Ayres et al. 1996). Ayres and Martiñas (1995) also argue that the exergy of waste streams is a proxy for their potential ecotoxicity or harm to the environment, at least in general terms.

From an accounting perspective, exergy is appealing because it is based on the science and laws of thermodynamics and thus has a well-established system of concepts, rules, and information that is widely available. But like weight for materials and enthalpy for fuels, exergy is not an appropriate basis for aggregation in economic indexes of IU because it is one dimensional. Like enthalpy, exergy does not vary with and hence does not necessarily reflect other attributes of fuels that determine their economic usefulness, such as energy density, cleanliness, cost of conversion, and so on. The same is true for materials. Exergy cannot explain, for example, impact resistance, heat resistance, corrosion resistance, stiffness, space maintenance, conductivity, strength, ductility, or other properties of metals that determine their usefulness. Like prices, exergy does not reflect the external costs of fuel use. The exergy of coal, for example, does not reflect coal's contribution to global warming or its impact on human health. As Ayres and Martiñas (1995) note, the exergy of wastes is at best a rough first-order approximation of environmental impact because it does not vary with the specific attributes of a waste material and its receiving environment that cause harm to organisms or that disrupt biogeochemical cycles. Finally, although in theory exergy can be calculated for any energy or material in practice, the task of assessing the hundreds (thousands?) of primary and intermediate energy and material flows in an economy is daunting.

We conclude this section on quality by reemphasizing the point that many indicators of material intensity are used to ask socioeconomic questions: How much material does it take to produce a unit of economic output? Is the economy dematerializing? These questions have an important economic component. Thus, we reiterate the main issue in the aggregation of material input: What is the best method to aggregate materials in the construction of economic indicators of sustainability, such as the material intensity of use? In its most common form, intensity of use is defined by dividing material use by GNP. GNP is an aggregate indicator of output that reflects (albeit imperfectly) the multifunctional attributes of the countless goods and services produced and the countless expressions of preferences exhibited in the market. An aggregate indicator of material inputs must do the same if the ratio of the two is to have any meaning. That is, the aggregate indicator must reflect the multifunctional attributes of materials that users consider when using them to produce and consume goods and services. The choice of materials by end users is in part an economic decision determined by relative prices, technology, income, and preference for specific attributes of the energy or material. It is reasonable, therefore, to expect that an index of aggregate energy or material use should reflect the partial but imperfect substitutability among types and that the weights used to construct such an index should reflect the value that users place on various types of energy and materials. In this context we find that an economic approach such as Divisia aggregation has several important advantages over physical and biophysical approaches. Taken as a whole, Divisia aggregation embodies a much more tenable set of assumptions than does aggregation by exergy, weight, or volume. No method adequately reflects the external costs of energy and material use.

This conclusion does not obviate the usefulness of other methods in many applications where no aggregation is required. Exergy or mass are appropriate if the object of analysis is a single material flux. Physical units also are necessary to assess waste flows because the market does not, in general, evaluate those flows. Integrated assessment of material cycles within and between the environment and the economy is logically based on physical stocks and flows. Thus, for many aspects of industrial ecology and industrial metabolism, physical units provide meaningful information.

## Testing Underlying Hypotheses

Perhaps the most glaring deficiency in the dematerialization literature is the lack of rigorous hypothesis testing. As Wernick and Ausubel (1997) note, despite "multiple anecdotes to support the dematerialization process few studies have offered a systematic approach for testing it." They call for research to both advance the theoretical framework for dematerialization and for identifying means to validate it. Conclusions about dematerialization must be reached through scientific analysis that is grounded in the materials science, technology, and economics of the industry and that has been subject to rigorous empirical tests. To achieve this, competing hypotheses must be tested against the historical record using the most appropriate and powerful analytical tools available. Input-output analysis, econometrics, and dynamic modeling offer specific well-defined frameworks for quantifying dematerialization and IU and for explicit hypothesis testing. Each method has strengths and weaknesses, but they are the most widely accepted tools used by scientists to test hypotheses about data sets that describe real-world phenomena. Without the discipline of quantitative hypothesis testing and rigorous modeling, authors are free to make any argument to support their a priori opinions and beliefs.

Outside of the visual inspection of data, regression analysis has been the most frequently used method, so it deserves additional discussion. With the exception of the work by Labson (1995) and Labson and Crompton (1993), the regression analyses of IU or materials consumption should be viewed with great caution. The work of Ross and Purcell (1981), Roberts (1990, 1992), Jänicke and colleagues (1989), Moore and colleagues (1996), and Rogich (1993b) do not use widely accepted techniques to test whether the important assumptions underlying the classical regression model are met. For example, none of them use standard tests for the presence of serial correlation or heteroscedasticity, problems that frequently plague time series data.

Most of the analyses rely on $R^2$ values to judge the strength of their models (e.g., Roberts 1990; Rogich 1993b). But most econometricians reject the $R^2$ value as a reliable indicator of how well a regression tests the underlying hypotheses of a model. The assumptions of the classical regression model require that the series of dependent and independent variables be stationary and that the errors have zero mean and finite variance. The presence of nonstationary variables can produce what Granger and Newbold (1974) call spurious regression, namely a regression that has a high $R^2$ and "significant" $t$-statistics but whose results are without any economic meaning. Again, there are procedures to test for stationarity (Dickey and Fuller 1979) and regression techniques that deal with nonstationary data (Enders 1995). In this regard it is interesting to note that the only analyses to use state-of-the-art time series econometric techniques do not support the widely held notion of dematerialization, at least in the case of major metals (Labson and Crompton 1993; Labson 1995).

What about the large literature that relies on visual inspection of time series data to draw conclusions about trends in the IU of materials? When applied to a particular material, visual inspection of IU as a function of time or income by an analyst familiar with the material and the industries that use it can lead to useful qualitative insights into general patterns of use. Less convincing are specific conclusions about the driving forces behind the trends and their relative importance based solely on visual inspection of time series data. This is especially the case for hypotheses about the driving forces behind the trends in broad material aggregates (e.g., all major metals) and substitutions among different broad categories. Thus, claims that a substantial decoupling of economic production from material input has occurred (e.g., Larson et al. 1986) or is feasible (Factor 10 Club 1997) should be viewed for what they are: assertions that currently have little convincing empirical support.

## Critique of the Materials EKC

The initial research on EKCs suggested that some pollutants follow an inverted U curve with respect to income (Shafik and Bandyopadhyay 1992; Panayatou 1993; Shafik 1994; Selden and Song 1994; Grossman and Krueger 1995). These results have been extrapolated by some to be an omnipresent outcome of economic development. The theoretical EKC model consistently appears in reports from the United Nations Environmental Programme and the World Development Report of the World Bank (World Bank 1992) and in statements such as "the strong correlation between incomes and the extent to which environmental protection measures are adopted demonstrates that, in the longer run, the surest way to improve your environment is to become rich" (Beckerman 1992, 491).

These conclusions are the subject of considerable scrutiny by many analysts (Arrow et al. 1995; Stern et al. 1996) and special journal issues (*Ecological Economics* 1998; *Environment and Development Economics* 1996; *Ecological Applications* 1996). This body of work indicates the EKC hypothesis is just that: a tentative hypothesis about the relation between income and environmental quality. A number of unknowns, uncertainties, and errors have been identified:

- Many of the regression models that find the existence of an inverted U function may be misspecified or suffer from omitted variable bias. In particular, they omit important variables such as the composition of production and consumption, international trade, and the density of economic activity, to name a few (Kaufmann et al. 1998).
- Most improvements in environmental quality identified in EKC studies have been achieved in part due to specific environmental policies, which are indirectly related to income.
- The inverted U curve has been examined for only a few pollutants, usually those that have local health effects that can be

mitigated with existing technology at moderate economic expense.
- None of the EKC work has assessed the broad array of ecosystem services that underpin our biological and economic existence (Daily 1997).
- Different studies with similar data have produced different results (Elkins 1997).
- The existing work provides limited insight into the actual mechanisms that diminish pollution after particular income levels.

One or more of these issues characterize all the materials EKC work that was discussed previously. Income is the *only* explanatory variable used in these studies despite the fact that we know that material consumption is affected by a host of other factors (Radcliffe 1976). The results of studies that rely solely on the visual inspection of data (e.g., Malenbaum 1978; Larson et al. 1986; Grübler and Fujii 1991; Jänicke et al. 1997; de Bruyn and Opschoor 1997) must be viewed with caution because they do not rigorously test any underlying hypothesis. The regression models do not use appropriate tests of significance, do not test for the existence of conditions that lead to spurious results (e.g., heteroscedasticity), and they probably suffer from the omission of variables that represent important underlying processes and motivations (e.g., Rogich 1993b; Jänicke et al. 1989).

Thus, contrary to the sweeping claims of some analysts (Larson et al. 1986; Bernardini and Galli 1993) and *potentially* contrary to the seductive idea that growth itself is the antidote to energy and material problems (Beckerman 1992), the quality and quantity of evidence does not yet support the hypothesis that the materials EKC is an ironclad universal phenomenon.

## Environmental Issues

Because data on wastes and emissions are sparse relative to data on energy and material inputs, many researchers use IU and total material use as proxies for environmental impact (Ayres 1989a; Jänicke et al. 1989; Bernardini and Galli 1993; Simonis 1994; Hinterberger et al. 1997). A common presumption, usually presented without any supporting empirical evidence, is that a declining IU translates directly into a reduction in environmental impacts (e.g., Radetzki 1990; Bernardini and Galli 1993). The reasoning behind the presumed relationship seems plausible: A decrease in the amount of a material—measured in tons—that is extracted, fabricated, and consumed will decrease the amount of waste material released to the environment. There are many specific examples of changes in technology or substitutions that reduce waste material release to the environment. For example, some industries have substituted solvents that can be recovered and reused on site for solvents that produced residues that required off-site incineration (Graedel and Allenby 1995). The decarbonization trend observed in many industrial nations is due to new energy technologies that release less carbon per heat unit (Grübler 1994a). There are many other examples.

Yet at an *aggregate* level we cannot assess with any precision the net environmental benefits reaped from the dematerialization we have observed. Every substitution and technical change that changes the types and quantities has a unique set of environmental impacts. There are many examples or suggestions of where “less” may not be less from an environmental perspective:

- The substitution of aluminum for steel and plastic for lumber could be a net loss for the environment. Bauxite mining has damaging environmental impacts and aluminum production uses enormous amounts of energy. Plastics currently are made from fossil fuels and pose significant recycling and disposal problems (Frosch 1995).
- The increasing use of specialty metals in electronics may lead to greater dissipation because many of the end uses are highly dispersed (Ayres 1989a).
- The substitution of tanned leather for rawhides produced garments and tools that were more comfortable and durable but also produced such pollution and disease that tanneries had to be separated from the communities they served (Frosch and Gallopoulos 1989).
- Lighter cars burn less gasoline, but steel is easy to recycle, whereas the composite plastics that have replaced it resist recycling.

Thus, fuel consumption drops, but there may be an overall increase in amount of permanent waste produced and resources consumed (Frosch and Gallopoulos 1989).

- If a reduction in weight of individual products is accompanied by a decrease in quality or durability, then more units will be produced, causing more depletion and pollution (Herman et al. 1989).
- The invention of the microchip and electronic storage of information and the substitution of personal computers for mainframes has proven to be paper using instead of paper saving as originally thought. People still prefer reading from paper; photocopy, fax machines, and personal computers make it easier to use paper, and uncertainty about long-term safety and security of electronic storage means that many primary transactions are still done on paper (Herman et al. 1989; Ross and Purcell 1981).

The upshot of these examples is that very thorough analysis of materials use—from extraction through disposal and recycling—must be done before we can conclude that a particular change in production or consumption improves environmental quality. The surge in interest in industrial ecology and metabolism is adding to our knowledge in this area, but we have a long way to go before aggregate assessments are possible, except for a few well-studied examples such as the aggregate decline in carbon intensity of GDP (Grübler 1994a).

But even when such assessments are available, we are still confronted with a formidable aggregation issue. A change in materials use is accompanied by a change in the qualities of material waste, the types of media to which they are introduced, and the type of ecosystem that is affected. Just as material inputs vary in quality from an economic perspective and thus should not be aggregated in terms of weight, material wastes vary in their potential for damage to the environment and human health. A substitution or technical change could reduce the total quantity of material waste but produce a quality of wastes that are more toxic or are released to ecosystems more sensitive to perturbation. Thus, in addition to information on quantities, we need some way of comparing the human or ecosystem health impacts associated with different material fluxes. Ecotoxicologists have well-developed procedures for comparing the toxicity of various chemicals to the health of humans and some aquatic ecosystems, but they are chemical- and media-specific. Ayres and colleagues (1996) propose exergy as a means of aggregating materials wastes and assessing their potential for harm. Although attractive due to the ability (in principle) to measure the exergy of every substance, this approach suffers from the same problem as the measurement of material inputs in mass terms: The potential ecological harm of materials does not vary directly with their exergy.

## What Can and Does MIPS Tell Us?

Hinterberger and colleagues (1997) argue that MIPS is a good indicator of the overall environmental impact of economic systems. In fact, they go so far as to say that MIPS is the "only measure introduced to date that can be used to compare relative environmental demands, and which can be translated directly into the realm of economics" (p. 8). Thus, they argue that MIPS is a reliable indicator of the efficiency with which materials are converted to GDP and of the impact that the mobilization of materials has on the environment.

It is likely that MIPS falls short of these lofty claims. Hinterberger and colleagues (1997) add all material flows together based on weight, whether they are tons of copper mined, tons of sediment eroded, or tons of $CO_2$ released to the atmosphere. They argue against the use of a weighting system to aggregate materials, claiming that they do not "see any practical and convincingly superior suggestion to weighting material flows in a more differentiated way" (p. 9). Let us examine this claim for both material inputs to production and material wastes.

As we stated earlier, the material intensity of GDP is an economic indicator. As such, aggregation of diverse materials by weight embodies untenable assumptions about the properties of materials on which users base decisions and hence about the possibilities for substitution among materials. From an economic perspective, aggregation by a Divisia or other type of index is clearly a superior, albeit imperfect, method of aggregation. This calls into question Hinterberger and colleagues' claim for the potential factor of ten reduction in material intensity that they claim is supported by empirical analyses of MIPS. In the case of material inputs to production, better indices of material aggregates need to be used to test the factor of ten hypothesis. Moreover, Hinterberger and colleagues' claim of a decoupling is not consistent with the work of Adriaanse and colleagues (1997), Labson and Crompton (1993), de Bruyn and Opschoor (1997), and others who suggest an ongoing strong link between material inputs and GDP.

We agree with Hinterberger and colleagues' (1997) statement that no reliable system exists for aggregating waste material flows according to their environmental impact. But it is unclear the degree to which an aggregate indicator based on weight conveys accurate and meaningful information about the level and trend in the ecological impact of society's waste stream. Just as weight often has little to do with why users choose one material over another, the environmental harm of a material often has little directly to do with its mass. As Hinterberger and colleagues note, the impact of a ton of plutonium obviously is far different from that of sand. Even for a given waste, the same quantity released to different media and different ecosystems in different locations will have different impacts.[5] Thus, it is entirely plausible that a decline in the total mass of wastes released could be accompanied by no change or even an increase in ecological impact due to qualitative changes in the waste stream.

We agree wholeheartedly with Hinterberger and colleagues on an important bottom line: The move toward a sustainable economy will require a reduction in the material footprint of society. MIPS has helped draw attention to this important point and provides a useful framework for analyzing the material fluxes associated with human existence. However, significant methodological hurdles remain before it becomes a reliable and unambiguous indicator of sustainability.

## Countervailing Forces: Rising Affluence and the Rebound Effect

As equations (1) and (2) indicate, the total use of a material, and to some extent the total waste that needs to be disposed of or recycled, is a function of IU *and* total output. It is entirely plausible for the IU for a particular material or for aggregate material use to decline, while total use increases due to growth in the consumption of products that contain the material. In this context, de Bruyn and Opschoor (1997) distinguish between "weak dematerialization" (a decline in IU) and "strong dematerialization" (a decline in total materials use). de Bruyn and Opschoor speculate that economic and technological limits may place an upper bound on improvements in energy and material efficiency. If true, sustained economic growth ultimately will increase energy and materials use due to diminishing returns to technical change and substitution. They attribute this phenomenon to the increase in their index of materials IU since the late 1980s (table 1).

Wernick (1994) and others note that population growth and rising affluence increase material use, offsetting substitution, technical change, and other forces that promote dematerialization. Industrial growth in Japan has more than offset the significant decline in the IU of fuels, electricity, and water in industry (Jänicke et al. 1997). Aggregate economic growth in the United States helped drive the consumption of wood products by enhancing the effects of an increased IU of paper and by offsetting a decrease in the IU of lumber (Waggoner et al. 1996). The decline in the IU of metals in telecommunications and broader electronics and computer markets brought about by miniaturization has been offset by the overall growth in these industries (Key and Schlabach 1986). Of course, the opposite effect also is possible; slower or negative growth can reinforce declining IU. Tilton (1990) and Roberts (1988) find that slower growth of the global economy helped reduce the demand for many metals by reinforcing the decline in their IU. Wernick (1994) suggests that we know little about the net effects of these countervailing forces for most materials.

Another important force that has received scant attention in the materials literature is the so-called rebound effect, which has been extensively documented and debated for energy. Distilled to its essence, the rebound effect applied to energy is this: Energy efficiency gains look to the consumer a lot like price reductions, spurring increased demand for energy either directly through price elasticity effects (e.g., people buying more gasoline when its price drops) or indirectly through released purchasing power redirected to energy-using goods and services (Saunders 1992). The implication is that one cannot look at just an individual material or an individual sector to assess the net benefit to the economy from improved energy or material efficiency. The effects of change in efficiency in one sector or for one resource ripple through the economy, affecting energy and material use in other sectors and in future time periods.

Theoretical and empirical evidence supports the existence of a significant effect for energy. Saunders (1992) uses a macroeconomic Cobb-Douglas and constant elasticity of substitution production function to show that, in general, energy efficiency gains increase energy use by making energy appear effectively cheaper than other inputs and by stimulating economic growth, which pulls up energy use. Several analysts have estimated the size of the rebound effect that is caused by gains in automobile efficiency in the United States. The effect is measured by the percent increase in miles driven associated with a 1% increase in the energy efficiency of automobiles. Values range from 0.05 to 0.40, with most estimates between 0.1 and 0.2. This means that 10–20% of the motor gasoline saved due to increased energy efficiency is "lost" by increased driving. Khazzoom (1980, 1987) claims that Lovins (1986) overstates the potential energy savings from more efficient appliances because he ignores the rebound effect. In a similar vein, Brookes (1990) argues that relying on energy efficiency to mitigate the greenhouse effect is fundamentally flawed because "reductions in energy intensity that are not damaging to the economy are associated with increases, not decreases, in energy demand." Lovins (1988) and Grubb (1990) take issue with the arguments of Khazzoom and Brookes.

We know little about the rebound effect for materials use, although in principle it should exist. One case study indicates that resource-saving technical change does not automatically translate into reduced demand for a resource. The results of Darwin's (1992) analysis of the lumber industry in the Pacific Northwest indicate significant sawlog-reducing technical change from 1950 to 1985. Thus, increasingly less wood input was needed to produce a unit of wood product. On the other hand, Darwin also found that the resource-saving technology did not lead to reduced harvests of timber in the region; in fact, the demand for sawlogs probably increased in the period. Clearly, this is an important area for future research.

## Imports

Most indicators of dematerialization and IU define material use in terms of apparent consumption of natural resource commodities. But societies also consume materials (and energy) that are embodied in semifinished and finished goods that they import and export materials and energy in a similar way. Thus, it is entirely possible that a decline (increase) in apparent consumption per GDP could be offset by varying degrees by an increase (decrease) in the net imports of materials embodied in goods.

We know very little about the magnitudes of these quantities. The International Iron and Steel Institute (1972) assessed the indirect steel trade for a number of countries in 1960, 1973, and 1982. Accounting for indirect steel trade altered the level and rate of change in the steel IU for all nations, sometimes dramatically, although in no case did it change the direction of change. Vanek (1963) analyzed the net trade of 20 major energy and material resources in the United States for select years from 1899 to 1954, including those embodied in goods. Vanek found that the United States steadily moved from a net exporter to a net importer of resources and that the net trade of many materials embodied in goods often was as large or larger than the direct trade of the materials themselves. Bringezu (1997) and Adriaanse and colleagues (1997) find that on a weight basis, the quantity of materials embodied in imported goods and services represent a significant fraction of total material use in industrial nations.

Given the ongoing expansion of foreign trade, this is an important area of research. With the enormous data requirements to calculate materials embodied in trade, this type of work is well suited to input-output analysis (Leontief et al. 1983), which can calculate quantities of materials imported and exported with estimates of the coefficients that reflect the material content of traded goods.

## Conclusions and Recommendations

Our literature review leads us to a number of conclusions. First, our knowledge of the extent of and mechanisms behind the patterns of material use are limited largely to individual materials or very specific industries, and most of those examples are metals. Second, the weight-based material intensity of the economy may be falling, but it is unclear what, if any, economic significance that trend has. Despite claims to the contrary, there is no compelling macroeconomic evidence that the U.S. economy is decoupled from material inputs. This derives in part from inappropriate measurement of aggregate material use and from the paucity of appropriate quantitative tests of the trends in overall material intensity and the driving forces behind those trends. Third, we know even less about the net environmental effects of many changes in materials use, except for a few important effects such as decarbonization. Thus, we agree with those analysts who argue that we should view with suspicion any gross generalizations about material use that are drawn from previous work, particularly the gut feeling that technical change and substitution inexorably leads to decreased materials intensity and reduced environmental impact (Auty 1985; Tilton 1989; Herman et al. 1989; Labson and Crompton 1993). Definitive movement in that direction would include (but not be limited to) dealing with the following issues:

- In general, there is a need for more quantitative empirical analysis that explicitly tests the myriad hypotheses about the driving forces behind the patterns of dematerialization and intensity of use of specific materials and material aggregates. It should explicitly represent demand shifts, technical changes, substitution effects, structural changes, or changing patterns of international trade and to the extent possible, quantify and separate the impact of these changes on materials use. A variety of modeling approaches are available: input-output methods, regression analysis, and systems dynamics models, to name a few.
- The analysis of time-series data must move beyond the visual inspection mode. By itself, the “biocular excitement test” cannot properly discriminate among competing hypotheses about the trend in an indicator or about the driving forces underlying the trend. Regression analysis must use standard techniques for testing the significance of model specification and results and for establishing the structure of the underlying data-generating process.
- The method used to aggregate materials should reflect relative material prices, technology, income, preferences for certain attributes, and the other economic criteria that users weigh when choosing materials. An index of aggregate material use should reflect the partial but imperfect substitutability among materials, and the weights used to construct such an index should reflect the relative value users place on various types of materials.
- Case studies should include a full accounting for the *net* environmental trade-offs of specific materials substitutions or technologies that alter the pattern of material use.
- More detailed assessments are needed of the overall effect of materials embodied in imported goods on the consumption of specific materials and aggregate materials.
- The hypothesis that a shift to a service economy produces significant dematerialization should be tested explicitly. This would include a full accounting of the direct and indirect use of materials in the provision of services.
- The degree to which aggregate economic growth and the “rebound” effect from in-

creases in the efficiency of materials use offset dematerialization, as is suggested by economic theory and some materials decomposition analysis, needs to be examined.

No doubt there are other interesting and important questions. This list provides a starting point for a new round of work that will build from the solid foundation of work in the past two decades.

## Acknowledgment

An earlier version of this article was prepared as a background paper for the Scientific Planning Committee, Programme on Industrial Transformation, International Human Dimensions Programme on Global Environmental Change. Robert Ayres, Jesse Ausubel, and two referees provided valuable comments on earlier versions.

## Notes

1. We define the term "aggregate" to mean two or more different materials added together in a measure of a material, stock, or flow. Aggregate in this context does not refer to inert materials such as sand or gravel used in construction.
2. Apparent consumption is defined as [domestic production + (imports – exports) + stock changes].
3. The name comes from the work of Simon Kuznets (1955), who postulated a similar relation between income inequality and income levels.
4. The OECD is an intergovernmental association comprised of industrialized democracies located predominantly in Europe and North America.
5. Editor's note: For a discussion of the incorporation of spatial differentiation into impact assessment, see J. Potting, W. Schöpp, K. Blok, and M. Hauschild, Site-dependent life-cycle impact assessment of acidification, *Journal of Industrial Ecology* 2(2): 63–87 (1998).

## References

Adriaanse, A., S. Bringezu, A. Hammond, Y. Moriguchi, E. Rodenburg, D. Rogich, and H. Schuetz. 1997. *Resource flows: The material basis of industrial economies*. Washington, DC: World Resources Institute.

Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C. S. Holling, B. O. Jansson, S. Levin, K. G. Maler, C. Perrings, and D. Pimentel. 1995. Economic growth, carrying capacity, and the environment. *Science* 268: 520–521.

Ausubel, J. H. 1996. Can technology spare the earth? *American Scientist* 84: 166–178.

Ausubel, J. H. and H. E. Sladovich (Editors). 1989. *Technology and environment*. Washington, DC: National Academy Press.

Auty, R. 1985. Materials intensity of GDP: Research issues on the measurement and explanation of change. *Resources Policy* 11: 275–283.

Ayres, R. U. 1978. *Resources, environment, and economics: Applications of the materials/energy balance principle*. New York: John Wiley and Sons.

Ayres, R. U. 1989a. Industrial metabolism. In *Technology and environment*. Edited by J. H. Ausubel and H. E. Sladovich. Washington, DC: National Academy Press, pp. 23–49.

Ayres, R. 1989b. *Technological transformations and long waves*. Laxenburg: International Institute for Applied Systems Analysis.

Ayres, R. and K. Martiñas. 1995. Waste potential entropy: The ultimate ecotoxic? *Economie Appliquée* 48: 95–120.

Ayres, R., L. W. Ayres, and K. Martiñas. 1996. *Eco-thermodynamics: Exergy and life cycle analysis*. Working Paper 96/04/ INSEAD, Center for the Management of Environmental Resources.

Beckerman, W. 1992. Economic growth and the environment: Whose growth? Whose environment? *World Development* 20: 481–496.

Bernardini, O. and R. Galli. 1993. Dematerialization: Long-term trends in the intensity of use of materials and energy. *Futures* 431–448.

Bringezu, S. 1997. Material flow indicators. In Sustainability indicators: Report of the project on Indicators of Sustainability, edited by B. Boldaun and S. Billhauz. New York: John Wiley & Sons Ltd., 168–176.

Brookes, L. 1990. Energy efficiency and economic fallacies. *Energy Policy* 10 (March): 783–785.

Brooks, D. B. and P. W. Andrews. 1974. Mineral resources, economic growth, and world population. *Science* 185: 13–20.

Carter, A. P. 1966. The economics of technological change. *Scientific American* 214: 25–31.

Cleveland, C. J. and M. Ruth. 1996. Interconnections between the depletion of materials and fuels: The case of copper production in the United States. *Energy Sources* 18: 355–373.

Cleveland, C. J., D. I. Stern, and R. K. Kaufmann. 1998. The aggregation of energy and materials in economic indicators of sustainability: Thermodynamic, biophysical, and economic approaches. *Ecological Economics*, in review.

Cochran, C. N. 1988. Long-term substitution dynamics of basic materials in manufacture. *Materials and Society* 12: 125–150.

Commoner, B. 1972. *The closing circle, nature, man, and technology*. New York: Alfred A. Knopf.

Considine, T. J. 1990. Recent trends in material consumption: The role of technology and economics. *Materials and Society* 14: 167–179.

Considine, T. J. 1991. Economic and technological determinants of the material intensity of use. *Land Economics* 67: 99–115.

Daily, G. C. 1997. *Nature's services: Societal dependence on natural ecosystems*. Washington, DC: Island Press.

Darwin, R. F. 1992. Natural resources and the marshallian effects of input-reducing technological changes. *Journal of Environmental Economics and Management* 23: 201–215.

de Bruyn, S. M. and J. B. Opschoor. 1997. Developments in the throughput-income relationship: Theoretical and empirical observations. *Ecological Economics* 20: 255–268.

Devine, P. R. 1988. *The effects of economic growth, technology change, consumption pattern change and foreign trade on domestic demand for primary metals, 1963–82*. Washington, DC: U.S. Bureau of Mines. PB89-204002.

Dickey, D. A. and W. A. Fuller. 1979. Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association* 74: 427–431.

Diewert, W. E. 1976. Exact and superlative index numbers. *Journal of Econometrics* 4: 115–145.

Duchin, F. 1994. Input-output analysis and industrial ecology. In *The greening of industrial ecosystems*, edited by B. Allenby and D. J. Richards. Washington, DC: National Academy Press, pp. 61–68.

Duchin, F. and G. M. Lange. 1994. *The future of the environment: Ecological economics and technological change*. New York: Oxford University Press.

Elkins, P. 1997. The Kuznets curve for the environment and economic growth: Examining the evidence. *Environment and Planning* 29: 805–830.

Enders, W. 1995. *Applied econometric time series*. New York: John Wiley & Sons.

Factor 10 Club. 1997. *Statement to government and business leaders*. Carnoules: Factor 10 Institute.

Fischman, L. L. 1980. *World mineral trends and US supply problems*. Washington, DC: Resources for the Future.

Fisher, J. C. and R. H. Pry. 1971. A simple model of technological change. *Technological Forecasting and Social Change* 3: 75–88.

Fortis, M. 1994. Economic growth and the intensity of use of industrial materials. In *Innovation, resources and economic growth*, edited by A. Q. Curzio, M. Fortis, and R. Zoboli. Berlin: Springer-Verlag, pp. 83–99.

Frosch, R. A. 1995. Industrial ecology: Adapting technology for a sustainable world. *Environment* 37: 16–37.

Frosch, R. A. and N. E. Gallopoulos. 1989. Strategies for manufacturing. *Scientific American* (September): 144–152.

Graedel, T. E. and B. R. Allenby. 1995. *Industrial ecology*. Englewood Cliffs: Prentice Hall.

Granger, C. and P. Newbold. 1974. Spurious regressions in econometrics. *Journal of Econometrics* 2: 111–120.

Grossman, G. M. and A. B. Krueger. 1995. Economic growth and the environment. *Quarterly Journal of Economics* 112: 353–378.

Grubb, M. J. 1990. The greenhouse effect: The fallacies in the energy efficiency solution. *Energy Policy* 783–785.

Grübler, A. 1990. *The rise and fall of infrastructures, dynamics of evolution and technogical change in transport*. Heidelberg: Physica Verlag.

Grübler, A. 1994a. Industrialization as a historical phenomenon. In *Industrial ecology and global change*, edited by R. H. Socolow, C. Andrews, F. Berkhout, and V. Thomas. Cambridge: Cambridge University Press, pp. 43–68.

Grübler, A. 1994b. Technology. In *Changes in land use and land cover: A global perspective*, edited by W. B. Meyer and B. L. Turner, II. Cambridge: Cambridge University Press, pp. 287–328.

Grübler, A. 1996. Time for a change: On the patterns of diffusion of innovation. *Daedalus* 125: 19–42.

Grübler, A. and Y. Fujii. 1991. Intergenerational and spatial equity issues of carbon accounts. *Energy* 16: 1397–1416.

Hammond, A., A. Adriaanse, E. Rodenburg, D. Bryant, and R. Woodward. 1995. *Environmental indicators: A systematic approach to measuring and reporting environmental policy performance in the context of sustainable development*. New York: World Resources Institute.

Hannon, B. 1982. Analysis of the energy cost of economic activities: 1963 to 2000. *Energy Systems and Policy Journal* 6: 249–278.

Herman, R., S. A. Arkekani, and J. H. Ausubel. 1989. Dematerialization. In *Technology and environment*, edited by J. H. Ausubel and H. E. Sladovich. Washington, DC: National Academy Press, pp. 50–69.

Hinterberger, F., F. Luks, and F. Schmidt-Bleek. 1997. Material flows vs. "natural capital": What makes an economy sustainable? *Ecological Economics* 23: 1–14.

Humphreys, D. 1994. Minerals in the modern economy. *Mineral Industry International*. July: 23–27.

Hutchinson, R. S. and J. E. Tilton. 1987. Is the intensity of copper use still declining in the USA? *Natural Resources Forum* 11: 325–334.

Ince, P. 1994. *Recycling and long range timber outlook*. U.S. Department of Agriculture Forest Service General Technical Report RM-242, Fort Collins, Colorado.

International Iron and Steel Institute. 1972. *Projection 85: World steel demand*. International Iron and Steel Institute.

Jänicke, M., H. Monch, T. Ranneberg, and U. E. Simonis. 1989. Structural change and environmental impact. Empirical evidence on thirty-one countries in east and west. *Environmental Monitoring and Assessment* 12: 99–114.

Jänicke, M., M. Binder, and H. Monch. 1997. "Dirty industries": Patterns of change in industrial countries. *Environmental and Resource Economics* 9: 467–491.

Jorgensen, D. W. and Z. Griliches. 1967. The explanation of productivity change. *Review of Economic Studies* 34: 249–282.

Kaufmann, R. K. 1992. A biophysical analysis of the energy/real GDP ratio: Implications for substitution and technical change. *Ecological Economics* 6: 35–56.

Kaufmann, R. K. 1994. The relation between marginal product and price in U.S. energy markets. *Energy Economics* 16: 145–158.

Kaufmann, R. K., B. Davidsdottir, S. Garnham, and P. Pauly. 1998. The determinants of atmospheric $SO_2$ concentrations: Reconsidering the environmental Kuznets curve. *Ecological Economics* 25: 209–220.

Key, P. L. and T. D. Schlabach. 1986. Metals demand in telecommunications. *Materials and Society* 10: 433–451.

Khazzoom, J. D. 1980. Economic implications of mandated efficiency standards for household appliances. *Energy Journal* 11: 21–40.

Khazzoom, J. D. 1987. Energy savings from the adoption of more efficient appliances. *Energy Journal* 8: 85–89.

Kondratiev, N. D. 1935. The long waves in economic life. *Review of Economic Statistics* 17: 105–115.

Kuznets, S. 1930. *Secular movements in production and prices: Their nature and their bearing upon cyclical fluctuations*. Boston: Houghton Mifflin.

Kuznets, S. 1955. Economic growth and income inequality. *American Economic Review* 45: 1–28.

Labson, B. S. 1995. Stochastic trends and structural breaks in the intensity of metals use. *Journal of Environmental Economics and Management* 29: S-34–S-42.

Labson, B. S. and P. L. Crompton. 1993. Common trends in economic activity and metals demand: Cointegration and the intensity of use debate. *Journal of Environmental Economics and Management* 25: 147–161.

Labys, W. C. and L. M. Waddell. 1989. Commodity lifecycles in U.S. materials demand. *Resources Policy* 15: 238–251.

Larson, E. D., M. H. Ross, and R. H. Williams. 1986. Beyond the era of materials. *Scientific American* 254: 34–41.

Lau, L. J. 1982. The measurement of raw material inputs. In *Explorations in natural resource economics*, edited by V. K. Smith and J. V. Krutilla. Baltimore: The Johns Hopkins University Press, pp. 167–200.

Leontief, W., J. C. M. Koo, S. Nasar, and I. Sohn. 1983. *The future impact of nonfuel minerals in the U.S. and world economy*. Lexington: Lexington Books.

Linde, D. R. (Editor). 1991–1992. *CRC handbook of chemistry and physics*, 72nd edition. Boca Raton, FL: CRC Press.

Lovins, A. B. 1986. Least cost energy strategies. Paper presented at the North American Meeting of the International Association of Energy Economists.

Lovins, A. B. 1988. Energy savings from more efficient appliances: Another view. *The Energy Journal* 9: 155–162.

Malenbaum, W. 1978. *World demand for raw materials in 1985 and 2000*. New York: McGraw-Hill.

McSweeney, C. and M. Hirosako. 1991. Understanding crude steel consumption. The perils of ignoring the role of technological change. *Resources Policy* 17: 258–270.

Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens. 1972. *The limits to growth*. New York: Universe Books.

Moldan, B. and S. Billharz (Editors). 1997. *Sustainability indicators*. New York: John Wiley & Sons Ltd.

Moore, D. J., J. E. Tilton, and D. J. Shields. 1996. Economic growth and the demand for construction materials. *Resources Policy* 22: 197–205.

Nakicenovic, N. 1986. The automotive road to technological change: Diffusion of the automobile as a process of technological substitution. *Technological Forecasting and Social Change* 29: 309–340.

Nakicenovic, N. 1990. Dynamics of change and long waves. In *Life cycles and long waves*, edited by T. Vasko, R. Ayres, and L. Fontvieille. Berlin: Springer-Verlag, pp. 147–192.

Nakicenovic, N. 1996. Freeing energy from carbon. *Daedalus* 125: 95–112.

Nappi, C. 1990. The food and beverage container industries: Change and diversity. In *World metal demand, trends and prospects*, edited by J. E. Tilton. Washington, DC: Resources for the Future, pp. 217–254.

National Commission on Materials Policy. 1973. *Material needs and the environment today and tomorrow*. National Commission on Materials Policy. Final Report.

Nieuwlaar, E. and W. v. Gool. 1990. Dynamic energy analysis of copper and aluminum production. *Materials and Society* 14: 117–142.

OECD (Organization of Economic Cooperation and Development). 1994. *Environmental indicators*. Paris: Organization of Economic Cooperation and Development.

Panayotou, T. 1993. *Empirical tests and policy analysis of environmental degradation at different stages of economic development*. Working Paper, Technology and Environment Programme, International Labour Office, Geneva, January.

President's Materials Policy Commission. 1952. *Resources for freedom*. Washington, DC: Government Printing Office.

Radcliffe, S. V. 1976. World changes and chances: Some new perspectives for materials. *Science* 191: 700–707.

Radetzki, M. 1990. *Economic growth and the environment*. Working Paper 90-10. Stockholm: SNS Energy.

Radetzki, M. and J. E. Tilton. 1990. Conceptual and methodological issues. In *World metal demand, trends and prospects*, edited by J. Tilton. Washington, DC: Resources for the Future, pp. 13–34.

Roberts, M. C. 1988. What caused the slack demand for metals after 1974? *Resources Policy* 14 (December): 231–246.

Roberts, M. C. 1990. Predicting metal consumption: The case of US steel. *Resources Policy* 16 (March): 56–73.

Roberts, M. C. 1992. The material composition of product and new materials. *Resources Policy* 18: 122–136.

Roberts, M. C. 1996. Metal use and the world economy. *Resources Policy* 22: 183–196.

Rogich, D. G. 1993a. *United States and global material use patterns*. Washington, DC: U.S. Bureau of Mines.

Rogich, D. G. 1993b. Material use, economic growth, and the environment. International Recycling Congress and REC'93 Trade Fair, Geneva, Switzerland, January 19–22.

Rogich, D. G. 1996a. Material use, economic growth, and the environment. *Nonrenewable Resources* 5: 197–210.

Rogich, D. G. 1996b. An analysis of material flow patterns in the United States and globally within the context of sustainable development. Directorate General for Environmental Protection, The Hague, Netherlands, Case No. 96.32.0043.

Ross, M. and Purcell, A. H. 1981. Decline of materials intensiveness: The U.S. pulp and paper industry. *Resources Policy* 7: 235–250.

Rostow, W. W. 1975. Kondratieff, Schumpeter, and Kuznets: Trend periods revisited. *Journal of Economic History* 35: 719–753.

Ruth, M. and B. Davidsdottir. 1997. *Impacts of energy and carbon taxes on the U.S. pulp and paper industry*. Working Paper Series, BU CEES 11-1-97. Boston, MA: Boston University Center for Energy and Environmental Studies.

Ruth, M. and P. Dell'Anno. 1997. An industrial ecology of the U.S. glass industry. *Resources Policy* 23: 109–124.

Ruth, M. and T. Harrington. 1997a. Dynamics of material and energy use in U.S. pulp and paper manufacturing. *Journal of Industrial Ecology* 1(3): 147–168.

Ruth, M. and T. Harrington. 1997b. Wastepaper repulping versus incineration in the U.S. pulp and paper industry: A dynamic systems analysis. *International Journal of Energy, Environment and Economics* 5: 151–182.

Ruth, M. 1998. Energy use and $CO_2$ emissions in a dematerializing economy: Examples from five U.S. metals sectors. *Resources Policy* 24: 1–18.

Saunders, H. D. 1992. The Khazzoom-Brookes postulate and neoclassical growth. *The Energy Journal* 13: 131–148.

Schmidt-Bleek, F. 1994. Revolution in resource productivity for a sustainable economy—a new research agenda. *Fresenius Environmental Bulletin* 2: 245–490.

Schumpeter, J. A. 1939. *Business cycles: A theoretical, historical, and statistical analysis of the capitalist process*. London: McGraw-Hill.

Seldon, T. M. and D. Song. 1994. Environmental quality and development: Is there a Kuznets curve for air pollution? *Journal of Environmental Economics and Management* 27: 147–162.

Shafik, N. 1994. Economic development and environmental quality: An econometric analysis. *Oxford Economic Papers* 46: 757–773.

Shafik, N. and S. Bandyopadhyay. 1992. *Economic growth and environmental quality: Time series and* *cross-country evidence*. World Bank. Background Paper for World Development Report.

Simonis, U. E. 1994. Industrial restructuring in industrial countries. In *Industrial metabolism, restructuring for sustainable development*, edited by R. U. Ayres and U. E. Simonis. Tokyo: United Nations University Press, pp. 31–54.

Spencer, V. E. 1963. *Raw materials in the United States economy: 1900–1961*. Bureau of the Census. Technical Paper 6.

Spencer, V. E. 1969. *Raw materials in the United States economy: 1900–1966*. Bureau of Mines and the Bureau of the Census. Technical Paper 30.

Spencer, V. E. 1972. *Raw materials in the United States economy: 1900–1969*. Bureau of Mines, Bureau of the Census. Technical Paper 35.

Spencer, V. E. 1980. *Raw materials in the United States economy, 1900–1977*. U.S. Department of Commerce, Bureau of the Census, Technical Paper 47.

Spencer, V. E. and C. A. R. Wardwell. 1954. *Raw materials in the United States economy: 1900–1952*. Bureau of the Census. Technical Paper 1.

Stern, D. I. 1993. Energy use and economic growth: A multivariate approach. *Energy Economics* 15: 137–150.

Stern, D. I., M. S. Common, and E. B. Barbier. 1996. Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development. *World Development* 24: 1151–1160.

Stigliani, W. M. and S. Anderberg. 1994. Industrial metabolism at the regional level: The Rhine Basin. In *Industrial metabolism, restructuring for sustainable development*, edited by R. U. Ayres and U. E. Simonis. Tokyo: United Nations University Press, pp. 119–162.

Szargut, J., D. R. Morris, and F. R. Steward. 1988. *Exergy analysis of thermal, chemical and metallurgical processes*. New York: Hemisphere Publishing Corporation.

Tilton, J. C. 1985. Atrophy in metal demand. *Earth and Mineral Sciences* 54: 15–18.

Tilton, J. E. 1989. The new view of minerals and economic growth. *Economic Record* 65: 265–278.

Tilton, J. E. (Editor). 1990. *World metal demand, trends and prospects*. Washington, DC: Resources for the Future.

Vanek, J. 1963. *The natural resource content of United States foreign trade, 1870–1955*. Cambridge: MIT Press.

Volland, C. S. 1987. A comprehensive theory of long wave cycles. *Technological Forecasting and Social Change* 32: 120–145.

Waggoner, P. E., J. H. Ausubel, and I. K. Wernick. 1996. Lightening the tread of population on the land: American examples. *Population and Development Review* 22: 531–545.

Wernick, I. K. 1994. Dematerialization and secondary materials recovery: A long-run perspective. *Journal of Minerals, Metals, and Materials Society* 46: 39–42.

Wernick, I. K. and J. H. Ausubel. 1995. National material metrics for industrial ecology. *Resources Policy* 21: 189–198.

Wernick, I. K. and J. H. Ausubel. 1997. *Industrial ecology: Some directions for research*. New York: The Rockefeller University.

Wernick, I. K., R. Herman, S. Govind, and J. H. Ausubel. 1996. Materialization and dematerialization: Measures and trends. *Daedalus* 125: 171–198.

Wernick, I. K., P. E. Waggoner, and J. H. Ausubel. 1997. Searching for leverage to conserve forests: The industrial ecology of wood products in the U.S. *Journal of Industrial Ecology* 1(3): 147–168.

Williams, R. H., E. D. Larson, and M. H. Ross. 1987. Materials, affluence, and industrial energy use. *Annual Review of Energy* 12: 99–144.

World Bank. 1992. *World development report 1992*. Washington, DC: World Bank.