Indicators of Dematerialization and the Materials Intensity of Use:

A Critical Review with Suggestions for Future Research

Cutler J. Cleveland[1]

Matthias Ruth

Center for Energy and Environmental Studies and Department of Geography
Boston University, 675 Commonwealth Avenue, Boston, MA 02215, USA
phone: +1-617-353-3083, fax: +1-617-353-5986, email: cutler@bu.edu; mruth@bu.edu

Background Paper for the Scientific Planning Committee, Programme on Industrial Transformation, International Human Dimensions Programme on Global Environmental Change, Amsterdam, The Netherlands, February 12-13, 1998

[1] Corresponding author

DRAFT: NOT FOR CITATION OR ATTRIBUTION

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Abstract

We review the definitions, meaning and major empirical analyses of the related concepts of dematerialization and intensity of use (IU). 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 (IU), which is the quantity of material used per unit of economic output. We organize our discussion around the central areas of research: 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 aggregate material use. We then discuss some outstanding issues such as the measurement of aggregate material use and aggregate waste emissions, the testing of underlying hypotheses, the importance of materials embodied in imports, and the forces that countervail dematerialization such as rising affluence and the “rebound effect.” Among our conclusions are 1) 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; 2) the economy is getting “lighter,” but the aggregate economic significance of that trend, if any, is unknown; 3) despite claims to the contrary, there is no compelling macroeconomic evidence that the US economy is “decoupled” from material inputs, and 4) we know even less about the net environmental effects of many changes in materials use, except for a few important effects such as the decarbonization of primary energy inputs. Thus, we agree with those analysts who argue that we should view with caution any gross generalizations about material use that are drawn from previous work, particularly the "gut" feeling that technical change, substitution, and ashift 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.

1. 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 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, 1989) 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 US 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, 1989; 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. Aggregate material use often is measured in terms of weight, which when compared to GNP in an index of the "efficiency" of material use probably has little economic meaning. Many analyses of dematerialization do not explicitly represent demand, technological change, or structural change, and they do not use methodologies that can test for the presence and relative strength of these forces (Auty, 1985). The techniques used to test for "trends" in time series and cross-sectional data often lack statistical rigor, with a few notable exceptions. 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). Finally, little attention has been paid to the offsetting effects of aggregate economic growth, and the "rebound effect," the potential for improvements in efficiency to actually increase material use. Thus, while 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.

The purpose of this analysis is three-fold. First, in Sections two and three 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 section four we discuss the major strengths and weaknesses of the research, with an eye towards what future research needs to focus on. Finally, in section five we pose some specific unanswered questions that could help shape the future research agenda in dematerialization. The focus here is on the US where the bulk of the work has been done, although a number of the studies reviewed include the US in international comparisons.

2. The 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 intensity of use (IU). Intensity of use often is 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):

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

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

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

The majority of 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 Section 4.

Intensity of use is determined by two quantities. The first term on the RHS of (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:

- 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 inter-material 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 towards 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 non-material 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 US 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.

3. The Theory and Empirical Analysis of Intensity of Use

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

3.1. *The Environmental Kuznets Curve for Materials*

The environmental Kuznets curve (EKC) is a widely-used indicator of sustainable development (World Bank, 1992).[1] The hypothesis underlying the EKC is that resource depletion and pollution tend to fall as incomes rise, producing an inverted U-shape function. 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 de-couple 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 towards 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 is explained by differences in their stage of economic development (Figure

[1] The name comes from the work of Simon Kuznets (1955) who postulated a similar relation between income inequality and income levels.

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* (1975). Malenbaum analyzed the IU for 12 metals in the world economy from 1951 to 1975, breaking nations into major groups and comparing them to the US. Malenbaum's index of IU was tons of metal per dollar of real GDP. Visual inspection of the data lead 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 de-coupled 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 et al. (1986) and Williams et al. (1987) build on this early work in their analysis of materials use in the US that culminates in their declaration that the "era of materials" is over. Larson et al. 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 reveal the inverse U shape, with the IU of even the "modern" materials now declining as a function of income.

Using a database on total materials use in the US 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, while 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 support the hypothesis that the US is shifting its preferences to lower density materials, but that "the consumption of materials is not declining as our standard of living improves."

Jänicke et al. (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 utilize 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 et al. 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 et al. conclude that a substantial "de-linking" occurred between material inputs and economic growth. However, they note that some eastern European nations showed increasing IU, while Japan and Norway experienced overall economic growth that "canceled" the improvements in the material IU.

Jänicke et al. (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 lead Jänicke et al. 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 et al. find that data for the US provide only "partial confirmation" of dematerialization, in this case made by a visual comparison of the absolute growth in GDP compared to absolute growth in the consumption of specific materials measured in tons. Steel, aluminum and cement declined relative to GDP, while paper increased.

de Bruyn and Opschoor (1997) question the conclusions of Jänicke et al. (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 et al. 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 et al.'s analysis with data from 1966 to 1990 for 19 nations. Their visual inspection of the data lead them to conclude that most nations did exhibit "delinking" from 1966 to 1984, but that some developed nations "re-linked" in the late 1980's, 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 US economy from 1800 to 1988 and find a nearly three-fold 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 inter-country differences explained by different degrees of industrialization, and hence differences in the technology and structure of industry.

3.2. 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 (Schumpeter, 1939; Kuznets, 1930; Kondriatiev, 1935). 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. When two technologies compete for the same market, logistic substitution models are applied in which the dynamic process by which a new technology replaces and old one is described by the changing fraction of the market held by the technologies.

The logistic substitution model has been used to model the growth of major transportation and communication infrastructures in the US (Grübler, 1990, 1996), the substitution of emissions controls in the US vehicle fleet (Nakicenovic, 1986), primary energy substitution in the US

(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 US, including synthetic for natural rubber, open-hearth for Bessemer steel, and synthetic detergents for soaps.

While 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 (1978) 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, while 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 et al. (1986) and Williams et al. (1987) apply this approach to the IU of metals and secondary materials in the US. They define IU in terms of weight per dollar GNP or per capita. Williams et al.'s (1987) visual inspection of the IU for 7 secondary materials and 10 metals in the US lead them to conclude that a substantial decoupling has occurred. They attribute the "maturing of basic materials" in the US 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 experience 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 lead 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 US 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.

3.3. *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:

$$\left(\frac{X_i}{Y}\right) = \left(\frac{X_i}{Q_m}\right)\left(\frac{Q_m}{Y}\right) \tag{3}$$

where Q_m is the Divisia index of aggregate material consumption. The first term on the RHS of equation (3) reflects inter-material substitution, while the second term results from inter-factor substitution. 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 US from 1960 to 1985. The aggregate materials IU (X_j/Y) showed no overall trend, while 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 percent in the decline in the IU for steel is due to inter-material substitution *(X/Q_m)*, four percent is due to inter-factor substitution *(Q_m/Y)*, and 16 percent 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 (1960-84), except for aluminum, suggesting that substitutions and technical changes driving that reduction could not explain the sudden slackening in demand after 1974.

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

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

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 US Bureau of Mines' forecast.

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

$$\text{Consumption} = (\text{Population})\left(\frac{\text{GNP}}{\text{Population}}\right)\left(\frac{\text{Consumption}}{\text{GNP}}\right) \tag{4}$$

Waggoner et al.'s decomposition analysis reveals that total paper consumption grew at an average rate of four percent 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 et al. conclude that the decline in the IU for lumber is one reason for the expansion of forest area in the US that began in the 1920s.

Wernick et al. (in press) 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 US from 1900 to 1993. Their model is

$$\text{ForestAffected} = \left(\frac{\text{ForestAffected}}{\text{Wood}}\right)\left(\frac{\text{Wood}}{\text{Paper}}\right)\left(\frac{\text{Paper}}{\text{GDP}}\right)\left(\frac{\text{GDP}}{\text{Person}}\right)(\text{Population}) \tag{5}$$

The third term on the RHS of equation (5) is the IU of industrial products, measured in cubic meters per dollar of GDP. Wernick et al. 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 while GDP increased sixteen fold.

3.4. *Statistical Analysis of Intensity of Use*

Ross and Purcell (1981) analyze the trends in the IU of the US 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 1960-79 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 et al. (1996) analyze the IU of non-ferrous metals and construction materials in the UK and US, 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 while 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 UK. Moore et al. 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 US. Moore et al. speculate that other forces are more important determinants of IU, such as resource-saving new technology, materials substitution, and intra-sectoral 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. 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 US, Japan, the UK, and the OECD in the post-war 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 while 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 US and OECD from 1946-1992. Labson again emphasizes that previous analysis of IU based on trend analysis implicitly assume stationarity about a deterministic trend. 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 as deep nature as to impart a permanent influence on IU over reasonably interesting time horizons."

3.5. 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 material waste flows and recycling (Duchin, 1990; Duchin and Lange, 1994).

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 (1966) disaggregated materials into nine categories, covering all the major non-energy inputs to the economy. She found an overall decline in the quantity of materials and semi-finished 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 et al. (1983) develop an input-output model of the US and world economy to forecast changes in the use of non-fuel 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 non-metals. For the US economy as a whole, the authors forecast a decline in the IU for 14 out of 18 metals; the IU of all the non-metals 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.

3.6. *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 US 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 US paper and board consumption will increase by more than 70 percent from 1986 - 2040 while 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 US 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 wastepaper-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 US 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.

3.7. *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 series of updates (Spencer, 1954, 1963, 1969, 1972) of the seminal work by the President’s Materials Policy Commission (1952) on raw material use in the US. Spencer reports the real dollar value of all raw material consumption (materials, energy, and food) in the US from 1900 to 1977. Per capita consumption of all materials increased from $372 to $454 (constant 1972$). 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) reports the results of research by the US Bureau of Mines that is based on a comprehensive data base on materials consumption in the US 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), while 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 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 data base on the IU of some important materials in the US 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, while IU for timber, copper, steel and lead declined. For the entire US economy Wernick et al., 1996 found that IU as measured by weight per dollar GNP declined by one-third from 1970 to 1990. On the measurement issue, Wernick et al. (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 et al. 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 et al. conclude that individual items may be getting lighter, but they economy as a whole is physically expanding. Due to these issues, Wernick et al. 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 US 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 to 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 percent 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 et al. (1997) employ a similar approach in their comparative analysis of materials use in Germany, the Netherlands, Japan, and the US from 1975 to 1994. Adriaanse et al. 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, ands 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 towards 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).

4. Discussion

4.1. *Measurement of Aggregate Material Use*

In reviewing the work on long-run trends in material use, Landsberg (1976) observed that the absence of a common measure of materials use means that general arguments about the ability of substitution and technical change to dematerialize the economy rest on historical trends and and projections of single commodities. Substitution and other effects thus cannot be isolated. Landsberg concluded:

> ...it is probably not prudent to look at the possible existence of such long-run relationships—an intensity of use and decline law—as offering a way out of contemporary problems associated with materials production and use.

More than twenty years later the dematerialization literature is still based largely on time series of individual materials, usually measured in physical terms, which are used to argue for a materials EKC or some other pattern of IU. Unfortunately, the lack of attention to, and solutions for, the “common measure” problem have not prevented a proliferation of “decline laws” and other theories of long-run relationships.

There are obvious reasons why materials are commonly measured in physical units, usually weight. First, and probably most important, agencies such as the US 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 is based on weight. Second, 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). Insuring 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 et al. (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 indexes. Williams et al. (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, while 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 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.

There are clear instances where weight is an appropriate index of material use. One example is the IU of individual, narrowly defined materials or products such as Tilton's (1983) volume on material use in the tin-using industries. Another example is where weight is a desired feature, such as the use of concrete or lead as ballast in large cranes. However, as soon as you begin to aggregate across materials, or when weight is not an important design feature, aggregation by weight loses or distorts important information.

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 is imply 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 US 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. Since much of the basic infrastructure of the US 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 the widespread use of aggregation by weight, it is not clear what the economic foundation is for doing so. Remember, in most analyses of IU the question being asked is an economic one: how much of a material is required to produce a unit of GNP? At this point it is useful to note that the price per ton of various materials differs enormously (Figure 3).[2] Government policy, regulations, and cartels explain some of the price differentials, but certainly not the enormous ranges that exist. More fundamentally, price differentials are explained by differences in attributes such as physical scarcity, impact resistance, heat resistance, corrosion resistance, stiffness, space maintenance, conductivity, strength, ductility, and so on. Wipe away the market imperfections and the price per ton of materials would vary due to their different combinations of attributes. The different prices per ton of material indicate that users are interested in attributes other than mass. An aggregate index of materials based on weight ignores these other attributes.

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[2] The discussion here relies heavily on Berndt (1978) who provides a lucid discussion of the quality issue in the context of energy.

The variation in attributes among material types means that materials are not perfect substitutes for one another. If only mass mattered and if all materials were prefect substitutes, the market would tend to price all material types at the same price per ton. Thus, aggregation by weight has a very restrictive and unrealistic economic assumption: it assumes perfect substitutability among material types.

The choice of materials by end users is an economic phenomenon determined by relative material prices, technology, income, and preference for certain attributes. It is reasonable, therefore, to expect that an index of aggregate material use should reflect the partial but imperfect substitutability among materials, and that the weights used to construct such an index should reflect the relative value end users place on various types of 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

$$\ln M_t - \ln M_{t-1} = \sum_{i=1}^{n} \overline{w}_{it}\left(\ln M_{i,t} - \ln M_{i,t-1}\right) \tag{4}$$

where the w_{it} are the non-constant expenditure shares of the *i*th material component

$$w_{it} = \frac{P_{it}M_{it}}{\sum_{i=1}^{n} P_{it} M_{it}} \tag{5}$$

and

$$\overline{w}_{it} = \frac{1}{2}\left(w_{it} + w_{i,t-1}\right) \tag{6}$$

where the *P's* are the prices per ton of materials. Note that prices enter the Divisia index via cost or expenditure shares. The Divisia index permits variable substitution among material types without imposing any 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 multi-dimensional attributes of materials, just as GNP embodies the multi-dimensional attributes of the goods and services produced by an economy.

Aggregation with price information 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 materials is not a function of the quantities of non-material inputs used. This may be an unrealistic assumption in some cases. Also, while the Divisia index does not restrict substitution among materials, it does assume that the substitution possibilities among all material types and output are equal. We also know that material prices are distorted by a number of market imperfections. Taken as a whole, however, Divisia aggregation embodies a much more tenable set of assumptions than does aggregation by weight or volume.

The economic importance of accounting for quality has been demonstrated for energy. Berndt (1978, 1990) argues that the same restrictive assumption described above for materials exist when aggregate energy use is measured in physical units such as BTUs. Users choose among energy types based on their unique combination of qualities: weight, cleanliness, safety, volatility, amenability to storage, heat content, etc. Cleveland et al. (1984) and Kaufmann (1992) adjust fuels for their relative qualities in their analysis of the energy/GNP ratio in the US. The results of their regression analysis indicate that much of the decline in the IU of energy in the post-war period is due to the shift from coal to higher quality fuels such as oil, natural gas and primary electricity. Kaufmann (1992) finds similar results in Germany, the UK and Japan. Stern (1993) develops a Divisia index of aggregate energy use in the US and uses it in a multivariate autoregression model that tests for the importance of energy, capital and labor in producing GDP in the U.S. from 1947 to 1990. Stern finds Granger causality from quality-corrected energy use to GDP, suggesting that a decline in energy use results in a reduction in economic growth. No such relationship exists when energy is measured in BTUs.

It is worth emphasizing that the focus of this section is on the appropriate way to aggregate diverse material inputs for the purpose of analyzing the relationship between aggregate materials use and economic output. We argue that the simple summation by weight or volume is inappropriate for this purpose, but this does not vitiate the weight- or volume-based approach for other purposes. Accounting in physical units is useful and appropriate in some life cycle analyses, industrial metabolism (Ayres, 1989), and in the analysis of the use of specific materials. If we are interested in the issue of solid waste disposal, volume obviously has something relevant to offer. However, the economic concepts of aggregate material use and IU is best measured by an indexing procedure that is consistent with basic economic theory (Berndt, 1978).

4.2. *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 materialization 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, 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 et al. (1989), Moore et al. (1996), 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. A series is weakly or covariance stationary if its mean and all autocovariances are unaffected by the choice of the starting date for the series. 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 which use 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 of 10 Club, 1997) should be viewed for what they are: assertions that currently have little convincing empirical support.

4.3. *Critique of the Materials EKC*

The initial research on EKCs suggested that some pollutants follow an inverted-U curve with respect to income (Grossman and Krueger, 1992; Shafik and Bandyopadhyay, 1992; Panayatou, 1993; Shafik, 1994; Selden and Song, 1994. These results have been extrapolated by some to be a 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, p. 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, 1995, in press; 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 an 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., in press).
- Most of the improvements in environmental quality identified in EKC studies have been achieved in part due to specific environmental policies, indicating that income alone doesn't get the job done.
- The inverted U curve has been examined for only a few pollutants, usually those that have local health effects that can 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.
- Different studies with similar data have produced different results (Ekins, 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 in section 3.1. 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; Jänicke et al., 1997; de Bruyn and Opschoor, 1997; Grübler, 1991) 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 and 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.

4.4. *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, 1989; Simonis, 1994; Jänicke et al., 1989; Bernardini and Galli, 1994; Hinterberger et al., 1997). A common presumption, usually presented without any supporting empirical evidence, is that a declining IU translates directly to a reduction in environmental impacts (e.g., Radetzki, 1990; Bernardini and Galli, 1994). 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, 1989).
- 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, by 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 PCs 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 they are introduced to, 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 et al. (1996) propose exergy as a means of aggregating materials wastes and assessing their potential for harm. While 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.

4.5. What Can and Does MIPS Tell Us?

Hinterberger et al. (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 have on the environment.

It is likely that MIPS falls short of these lofty claims. Hinterberger et al. (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's 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 that users base decisions on, 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 et al.'s 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 indexes of material aggregates need to be employed to test the factor of ten hypothesis. Moreover, Hinterberger et al.'s claim of a decoupling is not consistent with the work of Adriaanse et al. (1997), Labson and

Crompton (1993) and de Bruyn and Opschoor (1997) and others that suggest an ongoing strong link between material inputs and GDP.

We agree with Hinterberger et al.'s (1997) statement that no reliable system exists for aggregating waste material flows according to their environmental impact, leaving weight as the only plausible basis for aggregation. But it is unclear the degree to which an aggregate indicator based on weight coveys 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 et al. note, the impact of a ton of plutonium obviously is far different than sand. Even for a given waste, the same quantity released to different media and different ecosystems in different locations will have different impacts. 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 to due qualitative changes in the waste stream.

We agree wholeheartedly with Hinterberger et al. on an important bottom line: the move towards 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, unambiguous indicator of sustainability.

4.6. *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, but that total use could increase due to growth in the consumption of products that contain the material or aggregate economic growth. 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 US helped drive the consumption of wood products by enhancing the effects of an increase 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 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.

There is theoretical and empirical evidence that supports the existence of a significant effect for energy. Saunders (1992) uses a macroeconomic Cobb-Douglas and CES 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 US. The effect is measured by the percent increase in miles driven associated with a one percent 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 to 20 percent of the motor gasoline saved due to increased energy efficiency is "lost" by increased driving. Khazoom (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 Khazoom 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.

4.7. Imports

Most indicators of dematerialization and IU define material use in terms of apparent consumption of natural resource commodities [domestic production + (imports-exports) + stock changes]. But societies also consume materials (and energy) that are embodied in semi-finished 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 US for select years from 1899 to 1954, including those embodied in goods. Vanek found that the US 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 larger or larger than the direct trade of the materials themselves. Bringezu (1997) and Adriaanse et al. (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.

5. 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 economy is getting “lighter,” but that trend has little aggregate economic significance. Despite claims to the contrary, there is no compelling macroeconomic evidence that the US 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 test competing hypotheses about the trend in an indicator or about the driving forces underlying the trend. Regression analysis must use standard techniques for the 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 tradeoffs of specific materials substitutions or technologies that alter the pattern of material use.
- More detailed assessments of the overall effect of materials embodied in imported goods on the consumption of specific materials and aggregate materials.
- Explicit test of the hypothesis that a shift to a service economy produces significant dematerialization. This would include a full accounting of the direct and indirect use of materials in the provision of services.
- A more thorough examination of the degree to which aggregate economic growth and the “rebound” effect from increases in the efficiency of materials use offset dematerialization, as is suggested by economic theory and some materials decomposition analysis.

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.

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6. Figure Legends

Figure 1. Definitions of dematerialization.

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.

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

Figure 1.

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, p. 171).

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

"...the change in the amount of waste generated per unit of industrial products" (Herman et al., 1989, p. 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, p. 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, p. 238).