Technological Trajectories and the Human Environment. 1997.
Pp. 135–156. Washington, DC: National Academy Press.

Materialization and Dematerialization: Measures and Trends

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INTRODUCTION

"Revenge theory" postulates that the world we have created eventually gets even with us, twisting our cleverness against us (Tenner, 1996). Helmets and other protective gear have made American football more dangerous than its bare predecessor, rugby. Widened roads invite more vehicles, which mitigate gains in average traffic speed and flow. In short, human societies face unintended and often ironic consequences of their own mechanical, chemical, medical, social, and financial ingenuity.

In 1988 Robert Herman, Siamak Ardekani, and Jesse Ausubel began to explore the question of whether the "dematerialization" of human societies is under way (Herman et al., 1989). At that time, dematerialization was defined primarily as the decline over time in the weight of materials used in industrial end products or in the "embedded energy" of the products. More broadly, dematerialization refers to the absolute or relative reduction in the quantity of materials required to serve economic functions.

Dematerialization matters enormously for the human environment. Lower materials intensity of the economy could reduce the amount of garbage produced, limit human exposures to hazardous materials, and conserve landscapes. From time to time, fears arise that humanity will imminently exhaust both its material and energy resources. Historically, such fears have proven exaggerated for the so-called nonrenewable resources such as metals and oil. Yet if the human economy were to carelessly metabolize large amounts of Earth's carbon or cadmium, the health and environmental consequences could be dire. Meanwhile, the so-called renewable resources, such as tropical woods, are proving difficult to renew when demand is high. Thus, a general trajectory of dematerialization would certainly favor sustaining the human economy over the long term.

Is dematerialization occurring? Certain products, such as personal computers and beverage cans, have become smaller and lighter over the years. However, revenge effects may still countervail. A vexing case is that total paper consumption has soared despite claims that the electronic information revolution would create a paperless office. Americans now use about a kilogram of paper per day on average, twice the amount used in 1950.

In this essay we report further analyses of materialization and dematerialization, mostly for the United States during this century, and lay the basis for a systemwide assessment. We segment our analysis to consider measurements: (1) at the stage of resource extraction and the use of primary materials, such as minerals, metals, and wood; (2) in industry and industrial products; (3) at the level of the consumer and consumer behavior; and (4) in terms of the waste generated. At each stage one can ask whether dematerialization is taking place, what drives it, and what are its future trajectories and their consequences. Our studies consider materials in absolute terms, per unit of economic activity (measured by means of gross national product, GNP, or its slight "domestic" variant, GDP), and per capita. We assess changes in both volume and weight.

Materials consumption is analytically less tractable than energy use. It cannot be satisfactorily reduced to single elementary indicators such as kilowatt-hours or British thermal units. To illustrate this point, a pound of gold cannot be simply compared with a pound of lead, to the frustration of the alchemists. And neither one can be easily compared with a pound of plutonium. Materials possess unique *properties,* and those properties provide value, define use, and have environmental consequences. To capture these and other interactions, we must consider an ensemble of measures under the rubric of dematerialization.

The pattern of materialization and dematerialization, and the database from which it is drawn, helps frame the new field of industrial ecology (Frosch, 1992). Industrial ecology is the study of the totality of the relationships between different industrial activities, their products, and the environment. It is intended to identify ways to optimize the network of all industrial processes as they interact and live off each other, in the sense of a direct use of each other's material and energy wastes and products as well as economic synergism. The macroscopic picture of materialization can help raise key research questions and set priorities among the numerous studies of materials flows and networks that might be undertaken. It puts these in a dynamic context of both technical and market change.

DEMATERIALIZATION AND PRIMARY MATERIALS

In analyzing primary materials, it is helpful to begin with a profile of the total "basket of stuff" that a human society consumes. For this purpose, let us consider first "demandite," an imaginary, composite material representative of the nonrenewable resources we use. Demandite reveals our elemental preferences. All the materials that make up demandite are quantified in terms of the total moles of each element (or selected compounds) they contain; demandite is characterized by the fraction of moles for each element or compound divided by the total mole number.

First proposed by Goeller and Weinberg (1976), demandite includes both the energy materials (the hydrocarbon fossil fuels: coal, oil, and gas) and other materials, such as iron, copper, sulfur, and phosphorus, that are mined and used in the production of goods. Demandite omits some (crushed) stone that is used to build roads and other structures; the amount mobilized is quite large (about 1 billion metric tons in the United States in 1990) but this stone resource is practically infinite, and its elemental composition is more or less the average of the Earth's crust. Following Goeller and Weinberg, we recalculated the percentage of moles of the composite materials in demandite for the United States for 1968 and estimated these percentages for 1990 (Table 1).[1]

The hydrocarbon compounds dominate demandite. They swelled from about 83 percent of US demandite in 1968 to over 86 percent in 1990. In fact, total US consumption of hydrocarbons in 1990 was over 1.9 billion metric tons (t) or about 7.8 t per capita (20 kg per capita per day). The extraction and use of

TABLE 1 Demandite (United States)

Elements and Compounds	Percentage of Total Moles 1968	Percentage of Total Moles 1990
Hydrocarbons	83.20	86.77
Silicon dioxide	12.33	9.35
Iron	1.30	0.64
Oxygen	0.61	0.76
Sodium	0.57	0.44
Chlorine	0.57	0.44
Nitrogen	0.47	0.67
Phosphorus	0.29	0.35
Sulfur	0.21	0.25
Calcium carbonate	0.15	0.10
Aluminum	0.15	0.13
Potassium	0.09	0.07
Copper	0.04	0.02
Zinc	0.02	0.01
Lead	0.005	0.004
Magnesium	0.004	0.003

SOURCES: Chemical Manufacturers Association (1991), US Bureau of the Census (1975, 1992), and US Bureau of Mines (1976).

hydrocarbons pose problems such as global warming and oil spills, as well as health threats from urban, vehicular, and groundwater pollution.

The carbon, not the hydrogen, of course, is the "bad" element in the environmental story. The "decarbonization" of the economy is thus clearly of paramount environmental importance. As discussed by Nakićenović (see Nakićenović, this volume), relative to GNP and energy production, decarbonization is occurring steadily. Yet absolute carbon consumption by weight in the United States grew at a compound rate of 1.8 percent per year between 1950 and 1993.

Excluding energy materials, US material flows, including crushed stone and all other physical materials as well as renewables (with the exception of food), amounted to about 2.5 billion metric tons in 1990 or about 10 t per person (28 kg per capita per day) (Rogich et al., 1993). Construction materials dominated with 70 percent of total apparent US consumption (Table 2). Materials in this category may be associated with local environmental issues as excavations and structures transform the landscape, for better or worse. A striking fact is that 30 percent of the industrial minerals consumed dissipated into the environment and thus were rendered practically unrecoverable.

TABLE 2 Nonfuel Materials Flows in the United States, 1990

Material Group	Apparent Consumption (10^6 metric tons)	Recycled Quantity (%)	Dissipative Use (%)	Postconsumer Waste (%)	Processing Waste (%)
Construction Minerals	1,746	8	2	8	4
Industrial Minerals	330	8	30	8	2
Metals	112	55	0.2	13	5
Nonrenewable Organics (e.g., plastics)	112	2	---	19	---
Renewable Organics (e.g., forest products)	231	8	0.4	34	---
Animal Products (e.g., hides)	2.2	1	76	2	1

NOTE: The recycled as well as other materials flows shown are those reported for the same year as the apparent consumption and do not account for the time lag associated with the actual reprocessing or other endpoints of those materials.
SOURCE: Rogich et al. (1993).

TABLE 3 Material Densities in Metric Tons/Cubic Meter

Air @ 20°C 1 ATM	0.00121
Spruce (avg.)	0.43
Oak (avg.)	0.68
Gasoline	0.68
Commodity Polymers	0.9–1.25
Water	**1.00**
Whole Blood	1.06
Bone	1.7–2.0
Concrete	2.3
Granite	2.7
Glass, common	2.4–2.8
Earth's crust (avg.)	2.8
Aluminum	2.7
Steel	7.8
Copper	8.9
Silver	10.5
Lead	11.3
Mercury	13.6
Gold	19.3
Platinum	21.4
Osmium	22.5

SOURCES: Giancoli (1988) and *Handbook of Chemistry and Physics* (1962).

Fluctuations but no trend in absolute consumption by weight of physical materials are evident for the United States for the past twenty-five years (Rogich et al., 1993). However, an assessment of consumption per unit of economic activity shows a dematerialization in physical materials of about one-third since 1970. The oil shocks of 1973 and 1979 appear to have ratcheted the ratio down.

A complete current accounting of materials consumption in America, including renewables, nonrenewables, and both energy and nonenergy materials, reveals a total of more than 50 kg per capita per day (Wernick and Ausubel, 1995). (We have excluded the consumption of water and air.) This equals about 20 t/yr. If we assume a constant consumption over eighty years, an individual American's lifetime consumption would be 1,600 t. If the average material has the density of water (Table 3), the volume of material consumed in one person's lifetime would be equivalent to a cube measuring about 13 meters on a side.

Disaggregation reveals that the intensity of use of diverse materials has

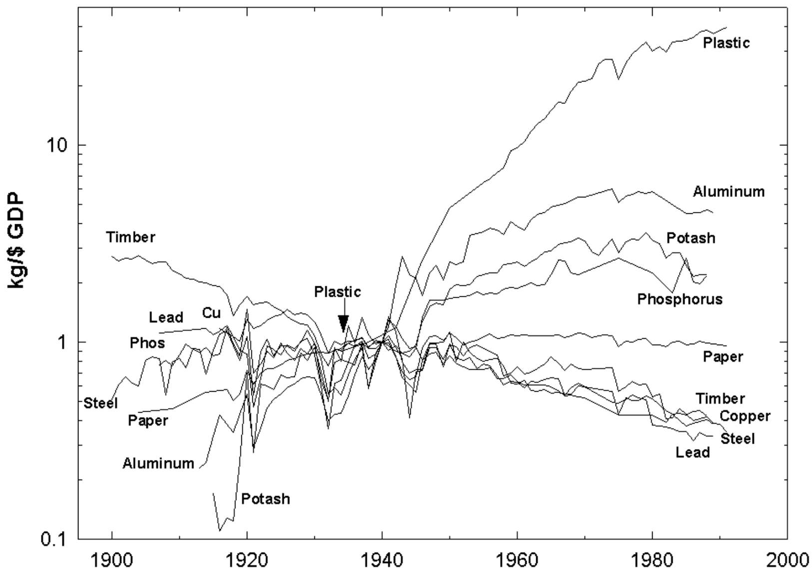

FIGURE 1 Intensity of use of materials in the United States. NOTE: Consumption data are divided by GDP in constant 1987 dollars. (For example, in 1907 the United States consumed 405,312 metric tons of lead and GDP was $371.28 billion, giving a ratio of about 1.09 metric tons of lead per million dollars GDP; in 1990 1,220,000 metric tons of lead were consumed and GDP was $4,152 billion, giving a ratio of about 0.29 metric tons per million dollars GDP.) For plastics we use production data only. DATA SOURCES: *Modern Plastics* (1960); US production of plastics resin, personal communication with Joel Broyhill, Statistics Department, Society of the Plastics Industry, Washington, D.C., August 20, 1993; US Bureau of the Census (1975, 1991, 1992, 1993, 1994, 1995); and US Bureau of Mines (various years).

changed dramatically over the twentieth century (Figure 1) (see also Ross et al., 1985). In terms of the weight of material used, normalized by GDP, timber sloped steadily down from its top position in 1900. Steel, copper, and lead also slid from their earlier heights. Plastics and aluminum followed upward trajectories, as did phosphates and potash, key ingredients in agricultural fertilizers.

Wood remained the preeminent material in the United States into the 1930s. It was used for fuel and as the structural material to build homes, workshops, vehicles, and bridges. It provided both ties and rolling stock for railroads as well as lamp, electric, and telephone poles for the utility infrastructures. Wood was gradually replaced by other materials and made more durable by creosote and other preservatives. Since 1930, annual US per capita consumption of commercial lumber has remained stable at about 200 board feet, down from about 500 board feet per capita at the turn of the century. An 80-foot spruce measuring 15 inches in diameter at breast height typically yields 200 board feet and is about sixty years old. The wood pile in earlier times was much larger, of course, because of the noncommercial use of wood for fuel.

In 1900, less than 2 percent of the timber cut in the United States produced pulp and paper. Today that fraction is over 25 percent. Absolute paper consumption has climbed steeply (Figure 2), while consumption per capita has risen more slowly. Amidst the electronic revolution, paper remains a preferred carrier of information. New technologies for information storage supplement the range and augment the amount of information stored, rather than reduce the use of paper. But, as Figure 2 also shows, paper consumption per unit of GNP has stayed essentially flat since 1930. During World War II, America briefly and drastically reduced its paper use relative to GNP or, rather, increased GNP without increasing its paper use.

Newly exploited materials now complement traditional ones, fortifying and enhancing their properties like vitamins. Materials such as gallium, the platinum-based group, vanadium, and beryllium have come into use in electronics and in the production of steel alloys and other "designer materials." The absolute amounts are small (10^{-4}–10^{-2} kg per capita per year) and relatively steady (US Bureau of Mines, various years). The small amounts of these new materials understate their importance both economically and environmentally. Extensive processing before final use may involve large ore bodies and mine wastes. Near

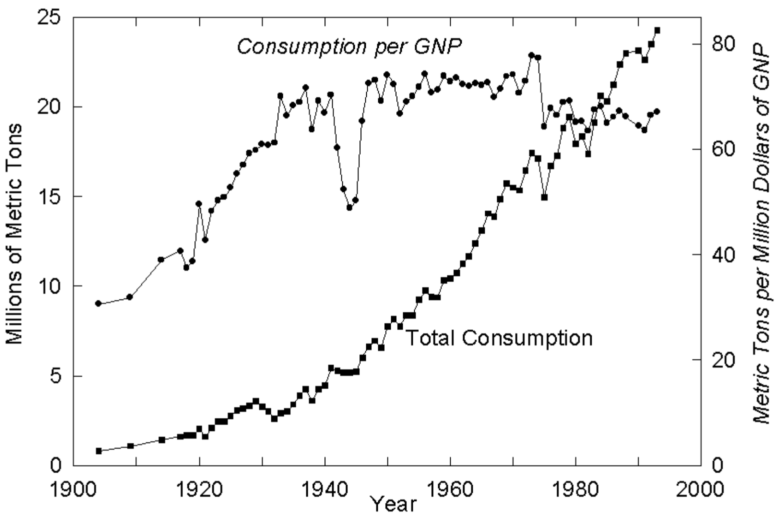

FIGURE 2 Absolute paper consumption and paper consumption per unit of GNP in constant 1982 dollars. DATA SOURCES: W. E. Franklin and Associates (1990) and US Bureau of the Census (1975, 1991).

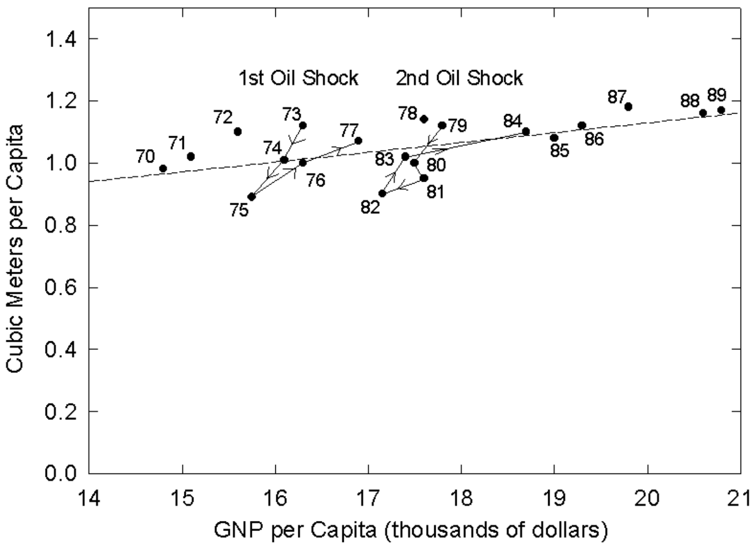

FIGURE 3 US per capita volumetric material consumption for wood/plywood products, paper/paper products, plastic, and metals plotted against GNP per capita in constant 1990 dollars. NOTE: Volume is calculated from average material densities. The solid lines show the short-lived effects of the oil shocks. The dashed line is a linear best fit to the historical data. SOURCE: After Rogich et al. (1993).

optimal use is then made of the elemental physical and chemical properties of the refined materials. Precisely because of their potency, these are distributed in small amounts that are sometimes difficult to recover, thereby frustrating efforts to recycle other materials "contaminated" by them.

Although the weight of materials employed may be stable or declining, the volume of materials is gradually increasing in the United States. Average density values (Table 3) can be combined with consumption data for individual materials to estimate the total volume of materials consumed. As shown in Figure 3, since 1970 volume per capita of the combination of paper, wood, metals, and plastics has increased along with economic growth, according to a linear best fit of the data and notwithstanding the oil price shocks of 1973 and 1979. Within five years of each shock, the system had resumed its long-term volumetric expansion. Individual items in the American economy may be getting lighter, but the economy as a whole is physically expanding.

Plastics, as a result of their increased consumption, account for much of the growth in volume; they are the preferred lower density materials. Polymer plastics are a "manufacturer friendly" material because they can be shaped into complex geometric forms with relative ease, are chemically inert, and can be created with a wide range of properties. Plastics have occupied market niches from car bumpers to soft-drink containers to furniture and plumbing parts.

Although commercial plastics were introduced early in the century (Bakelite, in 1909), they did not seriously enter the economy until 1940. About 500 billion kilograms of plastic have been produced so far in the United States, or, in terms of the current US population, about 2,000 kg per capita (*Modern Plastics*, 1960). Extrapolating the historical production, we estimate that the cumulative amount of plastic resin produced in the United States will roughly double by 2030. The primary feedstocks for plastic are oil, the dominant hydrocarbon, and, more recently, natural gas. One might say that plastics have been a by-product of the automobile. As long as cars run on oil, new plastic resin will be cheaply available. However, the decarbonization of the energy system and the growth of the plastic endowment will encourage much greater recycling of plastics over the next three or four decades, countering the mounting problem of plastic waste disposal. The high level of customization of plastics complicates matters, as this diversity makes effective separation and reuse more difficult.

DEMATERIALIZATION IN INDUSTRY AND INDUSTRIAL PRODUCTS

We can readily assess two relevant aspects of the materials used in industry: the dematerialization of individual end products and the use of recycled materials in production. More complete "life-cycle analyses" of products must embrace such partial examinations and extend them. For example, knowing the complete material and energy demand of a typical milk container throughout this century would be revealing. At present, we are unaware of life-cycle analyses repeated over time that provide an indication of trends.

Several individual end products manifest dematerialization. Containers, for example, have generally become lighter. At mid-century, beverage containers were predominately made of steel or glass (US Bureau of Mines, 1990). In 1953 the first steel soft-drink can was marketed. The public accepted it, resulting in the erosion of the market share of the heavier glass containers. Cans of aluminum, a material one-third the density of steel, entered the scene a decade later and grew from a 2 percent market share in 1964 to almost 90 percent of the soft-drink market and about 97 percent of the beer market by 1986. The aluminum can was itself lightened by 25 percent between 1973 and 1992 (Garino, 1993). In 1976, polyethylene terephthalate (PET) resins began to occupy a significant portion of the market, especially for large containers, where glass had previously dominated.

Cars have also become lighter on average, although the recent sales growth of light trucks and sport vehicles counters this trend. The car is an interesting object for study because it represents a full market basket of the products of an industrialized economy, including metals, plastics, electronic materials, rubber,

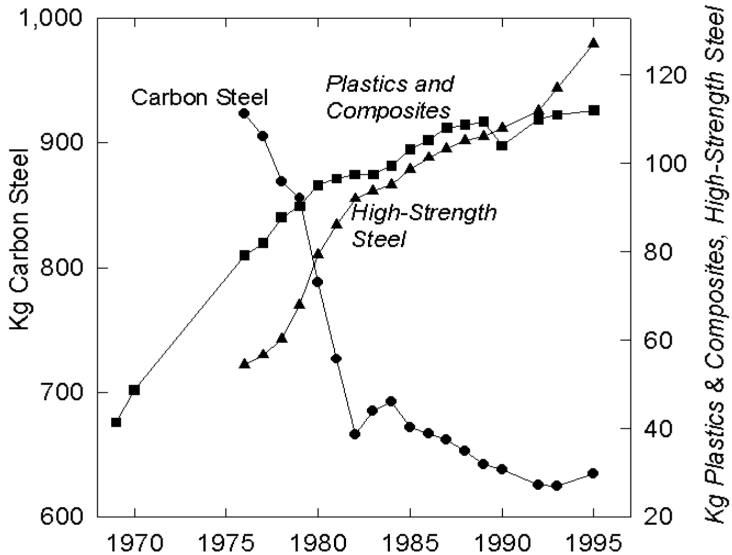

FIGURE 4. Changing weight of selected materials in the average US automobile. DATA SOURCE: *Wards Automotive Yearbook* (1969–1995).

and glass. Cars have become more materially complex as well, an important factor in the difficulty of disassembly and reuse. Only recently have legislative and engineering efforts, particularly in Germany, been directed toward the design and eventual production of car components that can be replaced and recycled with minimal effort. In the early 1970s, the amount of carbon steel in the average US car began to decline and then fell sharply by about 300 kg or 35 percent (Figure 4). A combined increase of about 100 kg in plastics and composites and in high-strength steel helped "downmass" the automobile while maintaining its structural integrity, with the new materials substituting for the old in a ratio of about one to three.

Although aircraft use a tiny fraction of all materials, the aerospace sector, where performance demands are exceptionally stringent, has foreshadowed trends that later appear in the rest of the economy. The drive to downmass aircraft while improving their performance has placed the aerospace industry at the forefront of materials research. Each kilo safely shaved in design saves both fuel and money. The aerospace industry provides the strongest market for composite materials of carbonaceous fibers mixed with aluminum and titanium, which have excellent strength-to-weight ratios. Materials with greater thermal resistance also yield higher performance. An increase of 80°C in the operating temperature of a jet engine can yield a 20 percent increase in engine thrust (US Bureau of Mines, 1990). Engines once formed from pure nickel now include nickel and cobaltbased superalloys, aluminum-lithium alloys, and ceramics, all having superior thermal properties. Specialized coatings and paints used on aircraft now provide significant environmental handling challenges. The mounting trend here is toward complexity, not only in the final product, but in the processing stage as well as ultimately in disposal.

The closure of materials loops through the reuse of materials complements the downsizing route to dematerialization. While smaller and lighter products can reduce the amount of materials required by future generations to operate the economy, reuse and recycling can also minimize fresh inputs and waste outputs (Wernick, 1994). At present, secondary inputs to production have difficulty competing with virgin materials in many markets.

Successful secondary materials recovery relies on two basic factors: ease of isolation of the desired materials and consumer demand for reprocessed materials. The difficulty of isolation explains why only 7 percent of cadmium-loaded waste was recycled from hazardous waste streams in 1986 (Allen and Behmanesh, 1994) and an even smaller fraction of arsenic and thallium. The ease of isolation explains why lead now enjoys a recovery rate exceeding 70 percent of its demand. Lead is used mainly for automobile batteries, which are readily separated from the general waste stream. Dissipative uses of lead (e.g., paint and gasoline) have been substantially curtailed over the last few decades. The supply of wastepaper, also easily separated, has proved responsive to market demand, with a growing number of paper mills now accepting this source of fiber.

Steel is another material that is readily separated. The secondary supply neatly meets the demand created in large part by the technology of electric arc steel production, which relies primarily on scrap inputs. Electric arc steel production has risen steadily throughout the century and now constitutes about 40 percent of all steel production. Trace contaminants in scrap piles may confound future gains in this method of steel production, however. Contaminants, such as zinc, can be problematic even at a level of tens of parts per million and can result in substandard finished steel.

Demand for secondary materials, like all demand, is to a large degree a function of price. Precious metals such as gold and silver are commonly recovered from circuit boards. However, even the recovery of precious metals has limits. In the late 1980s, platinum prices needed to exceed $500 an ounce to make platinum recovery from catalytic converters economical (Frosch and Gallopoulos, 1989). Energy prices can spark secondary materials recovery trends in opposite directions. Recycled aluminum requires only 5 to 10 percent of the energy necessary for primary production, and this difference has spurred secondary recovery when energy is costly. At the same time, cheap and plentiful energy is often the obvious technical requirement for economical reversal of the dissipation of many materials, even when diluted to concentrations found in sea water.

The fraction of the total production of given materials supplied by secondary materials recovery broadly indicates the extent to which the economy functions

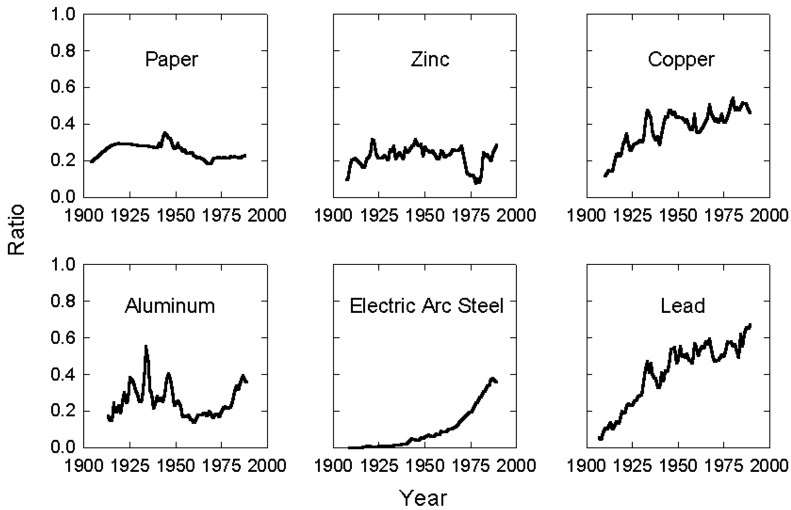

FIGURE 5. Ratio of production for secondary to primary sources of paper, zinc, copper, aluminum, steel, and lead in the United States. DATA SOURCES: US Bureau of the Census (1975, 1991).

with closed materials cycles (Figure 5). This measure shows little change for paper and zinc since early in the century. Copper rose rapidly in the early part of the century but has not been able to sustain an upward trend since 1940. Aluminum jumped in the late 1970s but may have plateaued again. Steel has climbed and points toward 50 percent. As noted, lead has surpassed 70 percent. World War II elicited peaks of materials reuse in the United States for several materials. These levels of reliance on recovered materials, often about 40 percent, may represent the current practical upper limit for many materials. The reasons appear to be not so much physical as economic. For example, suppliers of virgin materials can adjust their prices to undercut recycled supplies. Economic and population growth, of course, tend to draw new materials into the system.

DEMATERIALIZATION AND CONSUMERS

The number of consumers and their individual and collective behaviors drive materialization. An obvious fact is that there are more and more consumers. During the twentieth century the population of the United States has more than tripled, from about 80 million to more than 250 million. The absolute number is only part of the story. Life-styles also shape demand. Today, only a small fraction of consumption in wealthy nations (or communities) is actually for basic survival; most is for pleasure and to express one's standing in society.

Although fast modes of travel have enabled settlements to spread, Americans on average appear to be increasing the density of their built environment over time. An analysis of data from many diverse neighborhoods in Austin, Texas, indicates that the average size of a residential plot decreased between 1945 and 1985 (Figure 6). Meanwhile, the average floor area of an Austin residence increased by 50 percent or more. The fraction of a plot covered with a structure also increased by about 50 percent in both the mean and the aggregate.

A steady increase in land value over the years could contribute to the decline in plot area in some zones. "Market forces" may adjust the size of the plot area to reduce the impact of higher costs of land. In any new development, most of the land parcels are not portioned off by prospective buyers but rather by the developers. Hence, apart from making a binary decision whether or not to purchase, the buyer has limited influence on the subdivision planning and design process. The process of fixing the size of plots may be driven primarily by the economics of the situation as perceived by the developer.

Our hankering for a domicile in idyllic settings was what drove us to suburbia. Contrary to conventional belief, once we get there, we do not seem to care about how small the plot area is. Notwithstanding professed tastes for open space, we seem to build, enclose, and accrete steadily. We also seem to display a prefer-

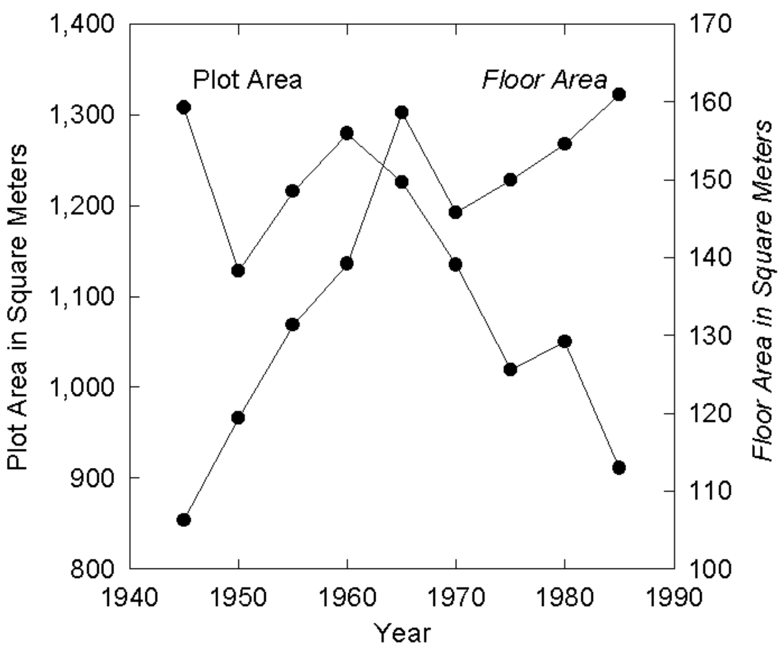

FIGURE 6 Size of average residential plot and floor area in Austin, Texas. NOTE: Data records for all single-family dwellings built during the period 1945–1990 in twenty-five of the twenty-nine zip codes within the Austin metropolitan area were used. DATA SOURCE: Austin Multiple Listing Service, Inc.

ence for larger and larger floor areas. This would also suggest that we have enough money to spend on larger houses or the material goods to fill up all the new (or "extra") floor area, but we are not perceived as having the desire to spend on larger plot areas.

Today's enlarged homes house fewer people. The number of residents per housing unit has declined monotonically in the United States from five in 1890 to fewer than three today (Figure 7). Interestingly, when the increase in floor area over time is viewed in conjunction with the decrease in the average number of residents per occupied housing unit, one could conclude that the *floor area available per person almost doubled in forty-five years.* This hypothesis should be treated with caution because it combines national aggregate data with data only for the city of Austin.

The trend toward larger floor areas housing fewer people implies that our consumption of building materials on a per capita basis is increasing, as is our requirement for energy services such as heating and cooling (see Schipper, this volume).

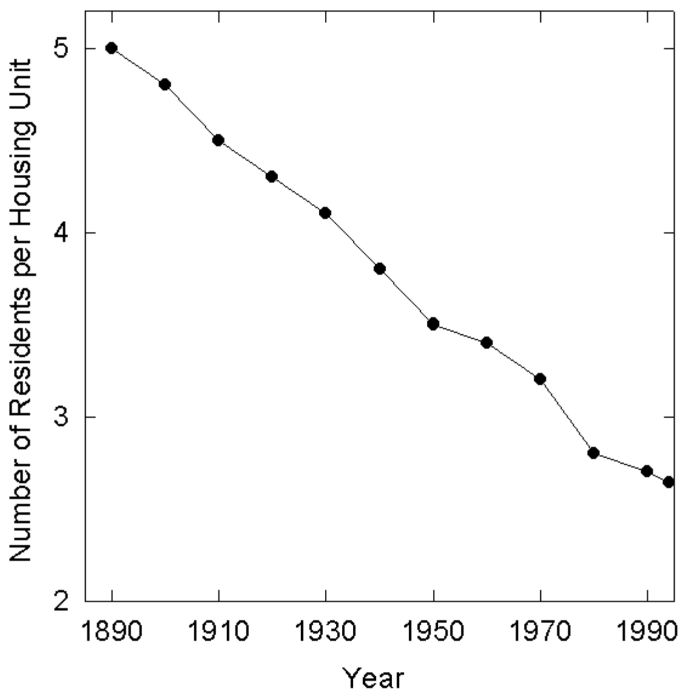

FIGURE 7 Average number of persons residing in an occupied housing unit in the United States (farm and nonfarm). DATA SOURCES: US Bureau of the Census (1975, 1995).

National data on the weight of household moves corroborates the Austin data of an increase in floor area. Data on the weight of household goods transferred in intercity moves implies that Americans on average possess more stuff over time. The average load increased by almost 20 percent to 3,050 kg (about a sixty-day stock of accumulated materials at the American rate of 50 kg/day) from 1977 to 1991 (personal communication from George Bennett, Statistics Department, Household Goods Carriers Bureau, Alexandria, Va., October 14, 1993). Intercity freight transport, measured in ton-miles, also aggregates a great deal of material. This measure indicates that as time goes by, Americans either ship more tons, ship each ton farther, or both. In 1990 Americans on average shipped freight 11,000 ton-miles; this compares with about 7,200 ton-miles in 1950. An increase in the weight, and therefore very likely the bulk, of possessions moved implies a need for more household space. Conversely, an increase in household floor space would always be filled by our insatiable appetite for possessions.

We also ship more information. The number of pieces of mail per capita in the United States has more than tripled since 1940 and stands today at more than 650 pieces per capita annually. Conservative estimates of the growth rate of electronic mail transmission and use in the United States is a phenomenal 10 percent per month. The information economy does not appear to substitute for the materials economy but may rather be required to manage its growth.

Whatever the reasons, from the vantage point of building materials, structures, and household amenities per capita, wealth appears to be a materializer. The shift from larger to smaller families materializes. Each housing unit is built of materials and in turn is filled with more objects to be used by fewer people.

The "individuation" of products also materializes. The dominant American social model is not simply to own one's home but to have access to products and services customized for more and more niches. Packages of "portion-controlled" prepared food and, more generally, product proliferation exemplify individuation. From 1980 to 1993 the number of new products introduced in supermarkets grew at an average compound rate of 14 percent per year. More than seventeen thousand new items appeared on store shelves in 1993 (personal communication from Lynn Dornblaser, Statistics Department, New Product News, Chicago, June 8, 1994).

Although many products saturate the consumer markets temporarily, they often rematerialize at a higher level. One example is the telephone. During the 1930s, telephones saturated in the United States at a rate of two for every ten persons (US Bureau of the Census, 1975). Starting about 1940, phones found new markets—the result of prosperity, new functions and fashions, and better performance. After 1970 it became difficult to keep track of the number of phones in operation in the United States. It is not surprising that the Bell System crumbled when it contained more than one hundred million objects at the level of the end user. Numerous phones now ring for every American. A continuation of this trend will bring the United States to many hundreds of millions of devices by

2020. On average each new generation of devices is smaller and lighter than its antecedents and performs more functions, such as fax transmission, voice mail, and wireless mobile telecommunications. An interesting question is whether the total mass of the telecommunications system, including cables and other equipment and facilities, has changed much since its initial formation earlier in the century. Revenge theory suggests that the overall system growth may offset the efficiency gains in its components.

DEMATERIALIZATION AND WASTES

Poor data, unreliable and inconsistent categorization, and infrequent surveys impede the establishment of waste trends (Rathje and Murphy, 1992; US Congress, Office of Technology Assessment, 1992). Serious interest in comprehensive rubbish data is quite recent. Moreover, some material by-products, which might otherwise flow into further productive use, become waste due to rather arbitrary labeling laws and regulations (see Frosch, this volume). One year for which comprehensive data for the United States are available is 1985 (Figure 8). Industrial wastes dominate, but 90 percent of industrial (including manufacturing) wastes can be water, so a comparison between classes may be misleading.

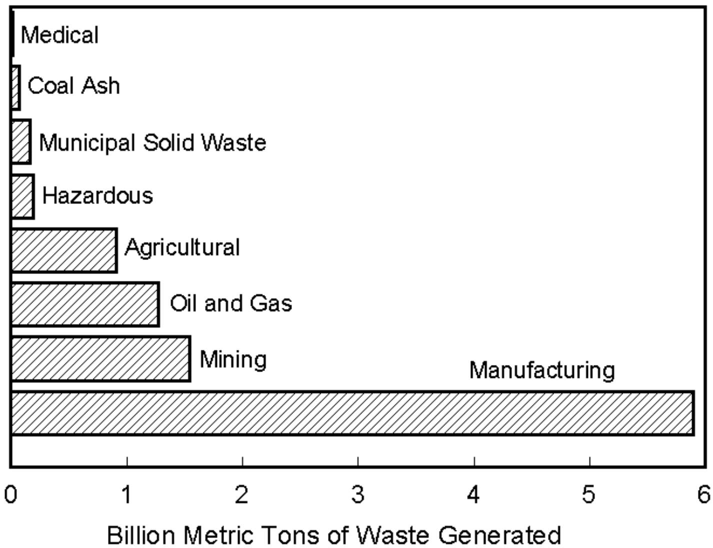

FIGURE 8 Major waste types by weight in the United States, 1985. NOTE: A large fraction of the total weight in the industrial categories is water. Dry weight of industrial wastes can be as low as 10 percent of the total. DATA SOURCE: US Congress, Office of Technology Assessment (1992).

When we simply add all of the wastes, the total in 1985 was about 10 billion metric tons, or about 115 kg per capita per day. Because a large and unknown fraction of this amount is water, it cannot be compared with our 50 kg per capita per day estimate of material use. Further research might lead to such a comparison and rough total guesses of net long-lived materialization. Instead, here we cautiously provide some comparisons of waste categories over time.

Sewage sludge almost doubled between 1972 and 1992 in the United States to 5.4 million dry metric tons, about 21 kg per capita annually (Jin, 1993). The increase does not indicate a change in human metabolism but rather in population growth and increased treatment of waste. The main source of *ash* is coal power plants. A rule of thumb is that about 10 percent of all coal burned remains as bottom ash, boiler slag, or fly ash captured by air pollution devices. As coal consumption declines, so does ash production, though flue-gas desulfurization may increase sludge while decreasing air pollution. Inclusion of coal and wood ash in historical analyses could substantially modify the picture of waste trends; it would flatten the recent rise by increasing the amount of waste generated in earlier periods. In 1990, the amount of coal ash produced equaled about 350 kg per American. *Hazardous wastes* include several hard-to-define subcategories, and no long-term figures are available (Allen and Jain, 1992). For such wastes environmental effects may sometimes be measured in micrograms rather than megatons. According to the US Environmental Protection Agency (EPA), in 1985 total hazardous waste generation was 271 million metric tons, while in 1987 it was 238 million, or roughly 1 t per capita. A related category is *toxic chemicals* and compounds released to air, water, and land by industrial facilities. Allowing for considerable uncertainty, EPA reports indicate that the total amount declined from about 2.2 million metric tons (4.8 billion pounds) in 1988 to 1.4 million metric tons (3.2 billion pounds) in 1992, or about 5.6 kg per American (INFORM, 1995).

In absolute terms, *municipal solid wastes* (MSW) in the United States rose from 80 million metric tons in 1960 to 188 in 1993, or about 725 kg per capita (US Bureau of the Census, 1995; US Environmental Protection Agency, 1992). About one-third of MSW by weight consists of packaging products. While MSW increased by about 1.5 percent per capita annually in the United States between 1960 and 1993, the amount of American trash generated per unit of GNP decreased, or dematerialized, on average by about 0.3 percent per year despite a recent upturn (Figure 9). As shown in Figure 10, reported waste generation varies markedly by country. Even among advanced industrialized nations, reported waste varies by up to a factor of three, which may partly reflect differences in categorization. The German data show a tight lid on trash, and in fact Germany seeks to reduce its packaging waste by 80 percent (Fishbein, 1994). Although it is hard to make global generalizations, the United States by all measures stands apart in its high level of trash generation.

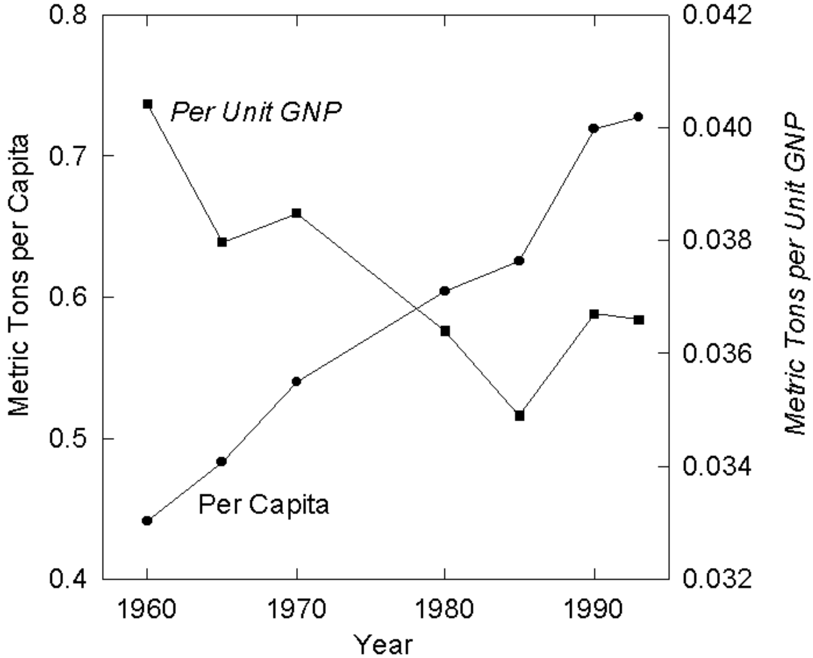

FIGURE 9 Municipal solid waste generation in the United States per capita and per unit of GNP in constant dollars. DATA SOURCES: US Bureau of the Census (1975, 1995) and US Environmental Protection Agency (1992).

QUESTIONS AND CONCLUSIONS

Is it possible to bring together existing evidence in a general theory of materialization and dematerialization? Bernardini and Galli (1993) have proposed a two-part theory that merits attempts at validation. The first part of their theory is that new materials substitute for old in subsequent periods of time (Fisher and Pry, 1971), and each new material shows improved physical properties per unit quantity, thus leading to a lower intensity of use. The second part of the theory applies to the development of nations or regions. The concept is that countries complete phases of their development sequentially at roughly the same value of per capita GDP, but the intensity of use of a given material declines depending on when each country completes its development, as the late-arriving economies take advantage of learning curves.

The Bernardini and Galli theory is hopeful for dematerialization. It implies that continued research and development of materials will bring about substantial gains and that global development will not dumbly imitate the behavior of the early developing nations. Thus, for example, China and India will never repro-

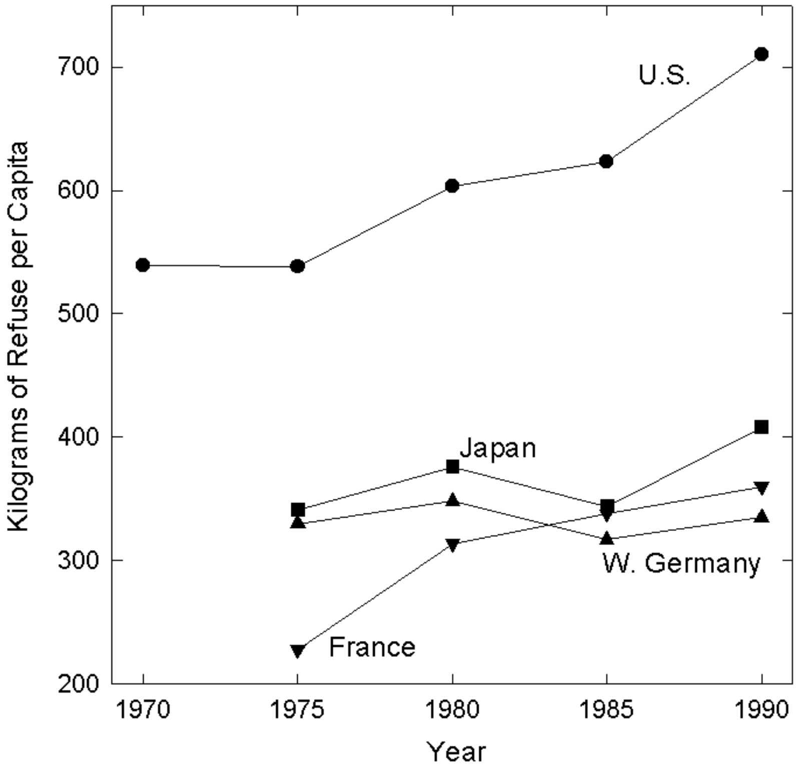

FIGURE 10 Refuse generation per capita for four industrialized countries. NOTE: Waste categorization and measurement vary considerably from country to country. DATA SOURCES: OECD (1991, 1994).

duce the pattern of per capita materials flows of the United States, even if their GDPs grow dramatically.

While appreciating this general logic for dematerialization, what does the actual evidence show so far for the United States? Our survey suggests the following:

(1) With regard to primary materials, summary ratios of the weight of materials used to economic product appear to be decreasing due to materials substitution, efficiencies, and other economic factors. The tendency is to use more scientifically selected and often artificially structured materials (Sousa, 1992). These may be lighter, though not necessarily smaller. The value added clearly rises with the choice of material, but so may aggregate use.

(2) With regard to industry, encouraging examples of more efficient materials use exist in many sectors, functions, and products. Firms search for opportu-

nities to economize on materials, just as they seek to economize on energy, labor, land, and other factors of production. However, the taste for complexity, which often meshes with higher performance, may intensify other environmental problems, even as the bulk issues lessen.

(3) As consumers, we profess one thing (that less is more) and often do another (buy, accrete, and expand). We see no significant signs of net dematerialization at the level of the consumer or saturation of individual material wants.

(4) With regard to wastes, recent, though spotty, data suggest that the onset of waste reduction and the rapidity with which some gains have been realized as well as the use of international comparisons indicate that very substantial further reductions can take place.

An overall assessment clearly requires an ensemble of measures under the rubric of dematerialization. System boundaries matter a great deal, whether they be nations, regions, economic sectors, firms, households, or products. In general, viewing the environmental impact of a product in isolation from the total system is simplistic. For example, examined in isolation, a computer could be deemed environmentally unfriendly because the production of the printed circuit boards, logic and memory chips, and display screens requires a large quantity of hazardous chemicals and solvents and heavy metals. This conclusion could also be based on its propensity for the consumption of paper and energy. However, the operation of the same computer in an industrial setting could increase efficiencies in a manufacturing process and reduce the consumption of energy and raw materials and the generation of waste. What a cursory scrutiny might identify as a local maximum could be a global minimum in terms of adverse environmental impacts. Thus, we must measure products, product life cycles, sectors, and the total materials economy at several stages, denominated in various ways.

A logical next step in research is to develop a self-consistent scenario for a significantly dematerialized economy and to explore the changes in technology and behavior needed to achieve it. Such an exercise should include careful examination of hazards as well as benefits to the environment associated with a qualitatively and quantitatively new materials economy.

Clearly, intensive research in materials science and engineering, sensitive to environmental properties, is a key to dematerialization. Humanity has passed from the ages of stone, bronze, and iron to an age in which we deliberately employ all ninety-four naturally occurring elements of the periodic table. We must learn to use the elements even better, in a way compatible with our long-term well-being.

In conclusion, we return to the observation that substantial progress has been made over the past century in decoupling economic growth and well-being from increasing primary energy use through increased efficiency. Decoupling materials and affluence will be difficult—much harder than decoupling carbon and prosperity. Objects still confer status, and they take their revenge.

ACKNOWLEDGMENT

We gratefully acknowledge assistance from John D. C. Little, Perrin Meyer, and Umer Yousafzai. We also thank the Austin Multiple Listing Service, Inc. and Borris Systems for providing access to their database of Austin residences.

NOTE

1. Our recalculation of demandite for 1968 differs from the results obtained by Goeller and Weinberg (1976). We believe that the discrepancy is due to our using different data inputs for calculating the silicate and calcium carbonate contributions to demandite. Our result of 12.33 percent for SiO_2 is slightly larger than their 11.15 percent figure, and our result of 0.15 percent form $CaCO_3$ is considerably smaller than their figure of 4.53 percent. We note that this disparity in results does not alter the conclusions drawn from the table, as it hardly affects the dominant position of the hydrocarbons, and environmental effects of these two minerals are essentially equivalent and benign.

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