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Consuming Materials: The American Way

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ABSTRACT

Sustaining the U.S. economy requires large inputs of materials, and their extraction, processing, and consumption affect the environment in many ways. In the United States, as in most industrialized countries, bulk materials consumption no longer runs in tanden with economic activity. Demand for raw materials in the richer countries has fallen well below the forecasts of decades ago, confounding predictions of dire shortage and reducing the projected income of countries that rely on mineral exports. Demographic shifts in the US and individual consumer preferences drive greater and more varied consumption. Saturated markets and technological advances offer promise for reduction. The success of large-scale materials recycling depends on the economics of secondary materials recovery and the suitability of secondary materials for reuse. Powerful social and demographic forces that draw more materials into the system will vie with technological innovations intended to limit inputs in shaping the future path of materials consumption in the United States.

Introduction

In the current social and political climate, whether meant to decry a pervasive "Coca-Cola" culture or more generally to assault the pace of economic and technological progress, "consumption" is a bad word [1, 2]. Consumption in the United States particularly offends, as one birth in Connecticut starts a path of consumption equal to 20 births in Mozambique. I leave to others the task of commenting on the vacuity of a materialistic culture and the confusion between technical and social progress. Rather, I will focus on characterizing consumption by providing an account of all the physical materials consumed in the United States and a framework for assessing the relative scales and environmental relevance of that consumption. Assessing the materials consumption of a nation requires viewing: (1) the total volume of materials consumed, (2) the composition of that total, (3) how these change with time, (4) forces driving those changes, (5) foreign trade in raw materials, and (6) the prospects for large-scale materials recovery. Together, these allow us to view materials consumption comprehensively and place particular instances and anecdotes in proper perspective. We shall not look at Barbie dolls and CD players but hope to gain insight on how they, and the demand for them, fits in the larger system.

National materials consumption indicates the structure of industrial activity and collective behavior. Environmentally important industries such as mining, forestry, agriculture, construction, and energy production can be evaluated based on their materials

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outputs and requirements. Human wants also map to materials consumption as people consume materials to provide shelter, food, power, mobility, and contact with others.

Since the oil price shocks of the 1970s, many have studied energy consumption at the national level [3, 4]. Such studies provide the analytic tools that have documented the slowing growth of primary energy consumption and its decoupling from U.S. economic development [5]. Though the analogy is imperfect, materials would similarly benefit from this approach but have not yet enjoyed the same scrutiny for several reasons. The same fear of imminent shortages that focused attention on energy has not been borne out with respect to materials. In the early 1950s, a U.S. presidential commission studying materials motivated by national security concerns concluded that even with economic growth, shortages would not materialize [6]. Studies in the 1970s, inspired by anxiety over limited global resources and projecting severe near-term shortages [7], were confronted with updated analyses again showing adequate supplies [8]. Actual increases in the amount of proven global material reserves in the intervening years have further confounded predictions of doom [9]. Though exhausting materials resources may in fact not be a priority concern – with the notable exception of high grade energy fuels – the environmental degradation resulting from extracting, processing, consuming, and disposing materials is.

The heterogeneity of materials consumed in modern society presents a further barrier to comprehensive analysis. Materials possess numerous and diverse properties that make them attractive to consumers and determine their environment l impacts, thus weakening generalizations. Whereas the energy from firewood, coal, or gas is readily reduced to common units such as joules or British Thermal Units, the utility of the gravel, ore, and fertilizer materials we consume cannot be. Furthermore, the materials industries are decentralized and difficult to circumscribe. Accordingly, the quality of data on materials suffers from gaps and problems with classification.

Though less than an ideal measuring stick, mass will serve here as the common currency for describing materials. Using mass alone may obscure important variables such as volume, toxicity, and land use. Yet, kilograms and tons do provide a means for grasping the sheer quantities of bulk materials mobilized to serve society and the relative sizes of different materials classes. Moreover, most of the available data on materials are either given directly in mass or can be converted to it.

Current National Materials Consumption and Temporal Dynamics

In 1990, the average American consumed, or moved, over 50 kg of material per day [10]. This total includes all the materials input to the economy to serve functions from providing electricity to building roads to feeding cattle. To gain some perspective, the mass of municipal waste that Americans dispose of each day accounts for less than 5% of this daily quantity [11]. Figure 1 shows the total as a sum of the six major classes of materials. Almost 90% of total inputs go to providing energy, structures, and food. Inputs of water, if included, would raise the total many fold. Mining wastes (particularly for coal) are huge and represent a consequence of consumption mostly hidden from the public eye. The daily 50-kg quantity may be common to highly industrialized societies. In 1990, Japanese consumption also summed to a little over 50 kg per capita per day [12].

The mix of materials consumed changes over time. One clear example of this is per capita U.S. lumber consumption (Figure 2). At the turn of the century, wood provided building materials for homes and factories, ties and rolling stock for railroads, utility poles for telephone and power lines, and fuel. Today a large fraction of harvested wood (~40% including residues) goes to paper mills [13]. Though drastic reductions in con-

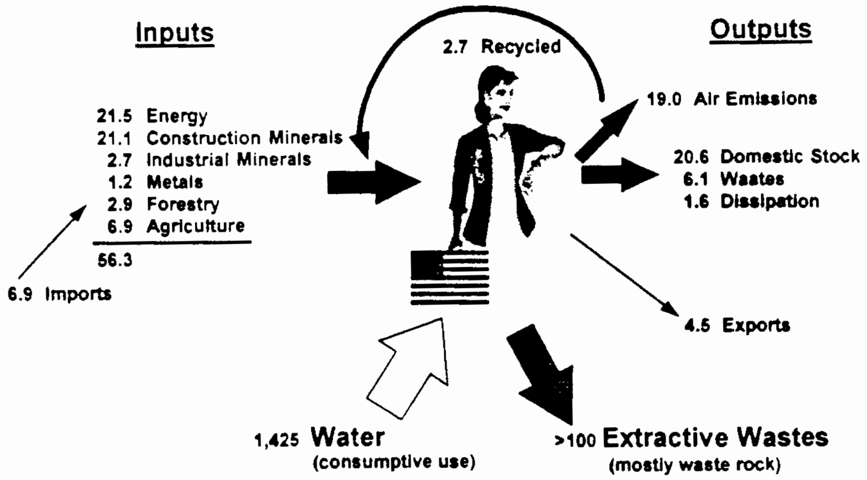

Fig. 1. Daily per capita material flows by mass (all values in kg): U.S. c. 1990. Materials are here classed as energy fuels (i.e., coal, oil, gas), construction minerals, industrial minerals, metals, forestry products, and agricultural products. *Source*: Wernick and Ausubel (see Reference 10).

sumption are more the exception than the rule, wood is not unique in that both the level of consumption and how it is used in the economy have changed.

A more aggregated account of consumption reveals wholesale changes in the amount of physical structure materials Americans consume. Figure 3 shows that in total tonnage per capita, reported consumption appears to rise over long cycles of economic growth then fluctuate during times of economic upheaval.

Are industrialized societies constrained to follow this path indefinitely? Do improvements in the standard of living necessarily translate to greater material consumption? Intensity of use (IOU) measures address this question directly. IOU measures show the evolution of individual materials used in the national economy by indexing primary, as well as finished, materials to gross domestic product [14]. Beginning with studies done in the late 1970s, researchers noted several common patterns in the course of consumption of a material in the economy [15]. Initially, the consumption of a particular material

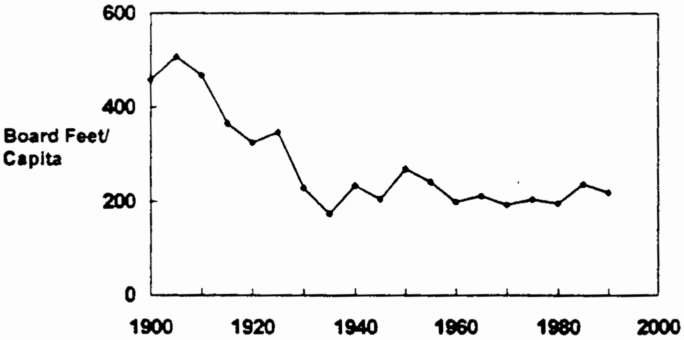

Fig. 2. Per capita lumber consumption: U.S. 1900–1990. (Note: Industrial roundwood, the more comprehensive measure of timber consumption, includes the categories of lumber, plywood, pulpwood, fuel, and logs) *Source*: U.S. Bureau of the Census (see References 22 and 23).

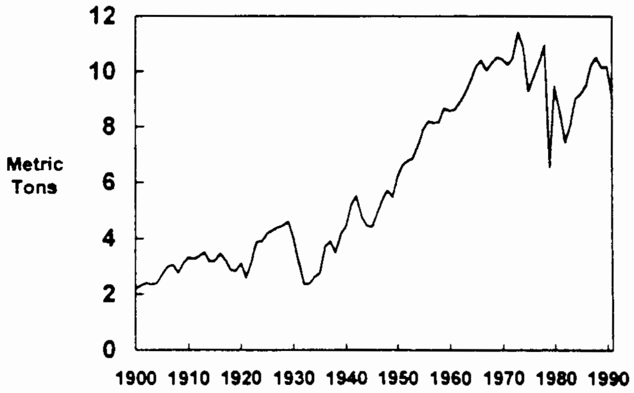

Fig. 3. Annual per capita consumption of physical structure materials: U.S. 1900–1991. Physical structure materials are here defined as construction minerals, industrial minerals, metals, forestry products, and animal products. *Sources*: U.S. Bureau of Mines Materials Consumption Database (unpublished); U.S. Bureau of the Census (see Reference 22).

exceeds general economic growth. Growing markets and newly discovered uses for the material stimulate further growth. This rapid growth eventually saturates, and consumption of that material then tracks or lags the rest of the economy.

Figure 4 illustrates this phenomenon at different stages for a variety of materials in the United States. One clear conclusion from the figure is that more dollars in the economy do not always mean more tons. Heavy materials such as steel, copper, lead, and lumber,

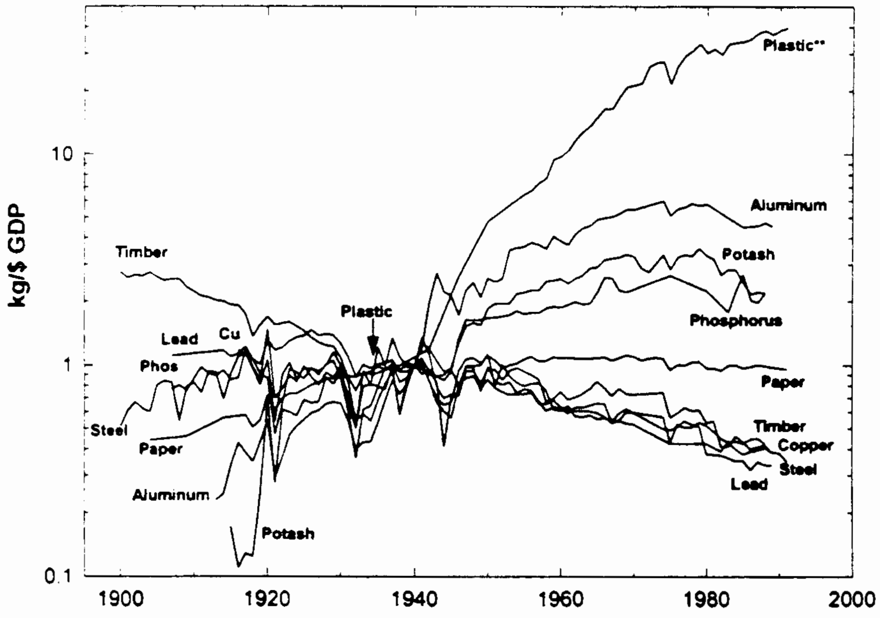

Fig. 4. Materials intensity of use: U.S. 1900–1990. Annual consumption data are divided by GDP in constant 1987 dollars and normalized to unity in the year 1940. Data for plastics are production data. *Sources*: U.S. Bureau of the Census (see References 22 and 23); *Modern Plastics* (Reference 24); plastics data from personal communication, Joel Broyhill.

TABLE 1
Major Materials Flows in U.S. Foreign Trade

Category	Exports (million metric tons)	Imports (million metric tons)	Net flow per capita (kg)
Agricultural products	135.5	14.9	(482.6)
Coal	96.0	2.4	(374.5)
Minerals	47.8	54.2	25.6
Metals and ores	27.0	76.4	197.8
Chemical and allied products	41.3	14.4	(107.6)
Petroleum products	34.1	96.9	251.3
Timber products	16.4	18.4	8.0
Paper and board	6.2	11.9	22.8
Oil (crude	5.6	307.4	1207.6
Natural Gas	1.7	31.0	117.2
Automobiles[a]	1.2	5.9	18.8
Total	412.7	633.8	884.4
Air transport	1.5	1.7	–
Waterborne transport	406.9	524.9	512.4
Trucks	151,000 (units)	766,000 (units)	N.A.
Other industrial and consumer products	?	?	

Source: U.S. Bureau of the Census (Reference 22).

[a] Based on an estimated average vehicle mass of 1.5 metric tons.

all materials used for infrastructures, became less critical to economic growth over the course of this century. Paper seems to track economic activity in lock step, conserving its role through the national shift from manufacturing to information and services. The rapid growth of materials used as fertilizers shows the "green" revolution that has raised agricultural yields. Finally, light-weight materials, such as aluminum, have outpaced economic activity in the second half of the twentieth century. This is spectacularly true with respect to plastics, a class of materials that in addition to being lightweight, possess a host of properties that make them the material of choice for the manufacturer and the consumer alike.

The types of material flows can be separated into the categories of elephants and fleas. Some of the bulk materials we have seen may be called the elephants. These high volume materials flows may cause little environmental impact per unit mass but can have profound long-range environmental consequences. Pumping oil, quarrying stone, and harvesting feed each contribute to chronic global environmental problems affecting atmospheric composition and land use. The fleas, materials generated in small quantities often as by-products of large-scale commercial production, can have more acute harmful effects. Consider that total annual U.S. dioxin releases are under 500 kg [16]. Despite the small quantity released, environmental concerns about the effects of dioxin continue to demand the attention of both government and industry. Using the U.S. Environmental Protection Agency's inclusive definition of "Toxic Release Inventory (TRI) production related wastes," toxic chemicals totaled about 17 million metric tons in 1992, 0.3% of all materials consumption [17]. Concerns over this relatively small mass fraction dominate much of the current public environmental debate.

Trade

Foreign trade in raw materials accounts for about 10% of U.S. materials flows. Table 1 shows that a few bulk commodities dominate trade. On a mass basis, agricultural

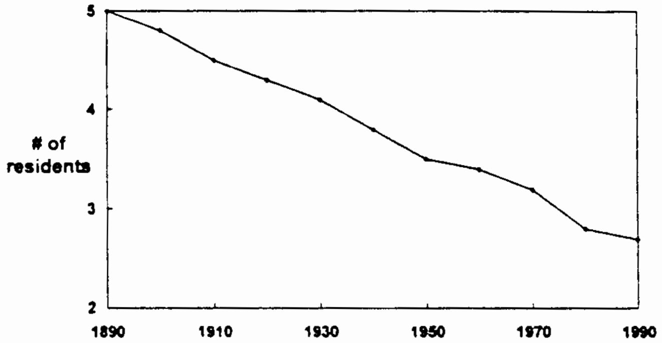

Fig. 5. Average number of persons residing in an occupied housing unit (farm and nonfarm), U.S.: 1890–1990. ***Source*: U.S. Bureau of the Census (References 22 and 23).**

products, coal, and chemicals dominate U.S. exports, whereas oil, oil products, and metals and ores dominate imports. Agricultural trade surpluses require domestic land, chemicals, and minerals, but feed many elsewhere.

For many minerals the United States shall continue to rely on foreign sources. Because most materials resources are widespread and abundant, nations and firms can be selective about where they mine [18]. Frequently, the decision favors initiating mining projects in the less developed countries (LDCs). For poor countries in the "South," such as Surinam, that rely heavily on mineral exports for their economy, the need for hard currency and the race to development can initially set aside environmental considerations. Several factors dim the prospect that mineral exports will finance general social and economic development in poorer nations. The mineral wealth of a region does not necessarily translate into wealth of the population, North or South. Perhaps more fundamentally, as the demand for raw materials in the industrialized nations continued to fall short of projections, world prices for raw resources have stagnated, allowing resources to flow North for static, or declining, reciprocal revenue streams [19].

Forces Affecting Materials Consumption

The simple arithmetic of a U.S. population of 400 million or more in 2100 will draw more materials into the economy [20]. Efficiency improvements might be able to maintain a constant total for the collective whole, in theory. However, in the U.S. more people means more individual consumers acting on their own. The average number of residents per American occupied housing unit halved since the beginning of the century (Figure 5).

Besides the materials needed for additional structures, appliances and furniture enter these dwellings irrespective of the number of inhabitants. Thus, the relationship of number of people to materials consumed is not simply proportional, reflecting settlement patterns as well. This same relation holds true for energy consumption: the same number of people living in a larger number of residences consume more [21].

Whereas American behavior drives expansion, historical development and technical innovations offer hope for contraction. The United States is a post-industrial country. The service sector continues to claim more of national economic activity, and the physical infrastructure of the country is largely in place. During the period 1970 to 1992, the surfaced road network in the United States, representing activities that consume massive

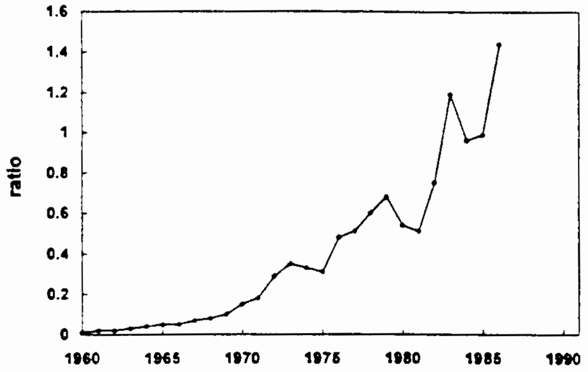

Fig. 6. Volume ratio of pipe manufactured from plastic over all other materials. *Source*: Hurdelbrink (Reference 35).

amounts of materials like steel, asphalt, sand, and rock, expanded at a third of the rate for the century [22, 23].

Substituting lighter for heavier materials also puts downward pressure on national materials use. Replacing heavy copper cable with light fiber optics not only reduces the amount of mass consumed but also reduces the need for mining copper ore. Lightweight plastics now provide the primary material for pipes, formerly made of steel and lead (Figure 6). The quantity of carbon steel in American automobiles fell drastically during the 1970s, while high strength steel alloys, plastics, composites, and aluminum continue to make up more of our cars (Figure 7).

For some products the same utility can be supplied with less mass of product. Metallurgical advances allow for steel beams with smaller cross-sectional area to support loads. Sweetening foods with high fructose corn syrup uses only a fifth the mass of sugar to produce the same result to our palate. The ubiquitous aluminum beverage can is today 25% lighter than in 1973 (Figure 8). In addition to smaller mass, the aluminum beverage can provides a model of a highly successful recycling system with a recycling rate exceeding 70%.

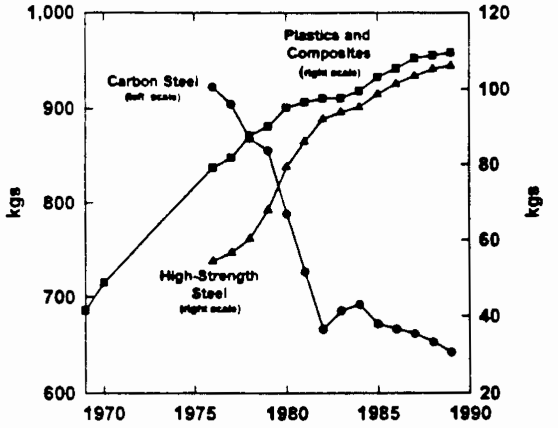

Fig. 7. Mass of carbon steel, high strength steel, composite materials, and plastics in the average U.S. automobile: 1969-1989. *Source*: Wards Automotive Yearbook (Reference 36).

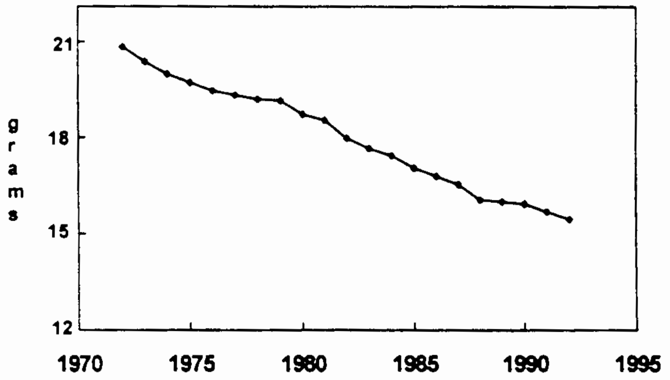

Fig. 8. Mass of Aluminum Beverage Can: U.S. 1973-1992. *Source*: Can Manufacturers' Institute, Washington, DC.

The combination of forces to reduce materials use in the industrialized countries drives a process that researchers have dubbed "dematerialization," or aggregate reductions in the amount of material needed to serve economic functions [24]. Substitution of materials that require less mass to deliver a unit of a given service, a phenomenon formally named "transmaterialization," represents a central component of the proposed shift to lowered consumption (Figure 9). Developing nations can benefit from the knowledge-based shift to lower materials requirements. The dematerialization hypothesis maintains that as nations launch into development later, their initial growth rates may be sharper but consumption saturates at lower levels as they can avoid the materials-intensive process of trial and error experienced by the earlier starters [25].

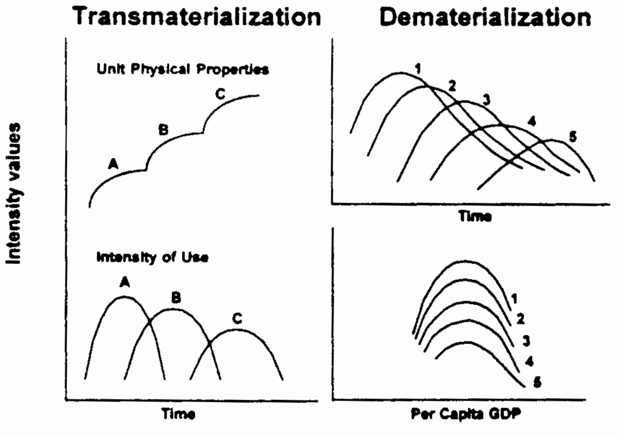

Fig. 9. (A): The process of transmaterialization described in terms of physical properties and raw materials use. New materials (A, B, C) substitute for old in subsequent periods of time. Each new material shows improved physical properties per unit quantity, leading to a lower intensity of use. (B): Figurative description of dematerialization. Countries 1-5 complete development in subsequent periods of time at roughly the same value of per capita GNP. The intensity of use of a given material declines the later in time each country completes development. *Source*: Bernardini and Galli (Reference 19).

Materials Recovery

Recycling, or more generally "materials recovery," accounts for about 5% of all U.S. materials consumption. For metals, the figure is over 50%, dominated by steel [26]. The preferences of consumers as well as the exigencies of producers heavily influence the size of this fraction. The heterogeneity of materials and goods entering the economy and the difficulty of later segregating them into their original components form the most severe problem. Just as the geologist must expect to find a practical concentration of metal to justify mining an ore body, so too profitable concentrations of materials in the waste stream are necessary to motivate and sustain recovery. Another obstacle lies in materials and goods that contain trace impurities in amounts sufficient to discourage recovery.

For consumer disposal, collecting, and sorting finished materials presents the major obstacle. Bulky appliances are relatively easy to collect for recovery of their ferrous and nonferrous metal fractions. Recovery, however, requires labor to remove contaminants such as PCBs and chlorofluorocarbons in old refrigerators and air conditions. Collecting discarded materials from U.S. households has met with mixed success. Obtaining relatively uniform and clean waste streams has proven especially difficult. Glass cullet containing amber, green, and clear glass, and plastics waste containing a mix of resins command much lower process than homogenous inputs. Waste streams containing dirty materials are also less attractive. U.S. state and local laws mandating percentage mass reductions in municipal solid waste have spurred automated material separation technologies that increase throughput and facilitate more recovery. Exploiting disparities in their physical characteristics, machines identify and separate materials based on magnetic and optical properties as well as density. Municipal recovery facilities that use these technologies require large initial capital investments, and the soundness of their economics remains a question.

Manufacturers hold great leverage in determining the mix of materials entering the system. By designing products to reduce packaging, avoid toxics, and ease disassembly, producers can help facilitate recovery from discarded products. For example, changing the aluminum beverage can from a three-piece to two-piece design and using compatible alloys for the component pieces eased the path to high recycling rates for that product. Perhaps the most important strategic change manufacturers can implement is to increase the uniformity of materials in consumer products, essential for the technical and economic success of material recovery.

Trace contaminants and alloying elements play a pivotal role in materials recovery. The electric arc furnace (EAF) steel industry, which relies heavily on scrap inputs, now encounters problems with "bad actors," elements such as zinc, chromium, and molybdenum added to steel to protect against corrosion, add strength, and modify other performance properties. These additives can cause defects in the finished steel if the scrap inputs contain them at levels as low as tens of parts per million [27]. One of the largest EAF producers in North America recently opened an offshore plant to supply virgin inputs to dilute and augment the charges entering their mills [28].

The second most consumed metal in the United States, aluminum, is also extensively alloyed to tailor properties for different applications. More than 20 different aluminum alloys are used in American automobiles [29]. Even if this nonferrous scrap is eventually isolated from a discarded automobile it cannot be melted down without downgrading to an inferior quality metal.

Many bulk materials generated within industry and far removed from the public eye show promise for reuse. Coal combustion by-products such as fly ash and sludge from sulfur removal now find uses in road construction and as residential building materials [30, 31]. Sand used in large quantities in industrial foundries is also being recycled [32]. One industrial park located in Kalundborg, Denmark has established a prototype for efficient reuse of bulk materials [33]. A petroleum refinery, power plant, pharmaceutical plant, wallboard manufacturer, and fish farm reside in the park. They exploit synergetic relationships by bartering waste energy and materials among themselves, leading to overall improved resource efficiency that contributes to each facility's bottom line.

Questions and Conclusions

Sustaining the U.S. economy requires consuming large amounts of materials. The mix of materials changes with time, and these changes matter from the perspective of environmental quality. The question of whether Americans will consume more or less materials in the future depends on demographic, economic, and technical variables difficult, if not impossible, to predict. One central question is: can increases in materials efficiency keep pace with or even triumph over the forces driving increased consumption? No single definitive answer exists, and those offered tend to reflect the predisposition of the respondent more than any objective truth. In the early 1800s, William Stanley Jevons predicted that the advent of more efficient steam engines would not diminish total British coal consumption. He was right. On the other hand, substitution, efficiency improvements, and the ascent of information and services as objects of value displaces the centrality of materials in the economy. Nevertheless, the diminished importance of heavy materials will not lead to reduced consumption without conscientious and concerted effort.

Toxics and other harmful materials constitute a small part of total consumption but are currently linked to the large-scale production of goods. They pose threats to human health and environmental quality far exceeding their mass fraction of materials consumption. To what extent these nasty residuals, often unintended byproducts of production, can be eliminated presents a further question.

For materials production outside the United States and the Organization for Economic Cooperation and Development countries, the headlong race to development in the least developed countries can relegate environmental concerns to secondary importance. This is exacerbated by the fact that these nations are struggling with weak demand from the North and slow revenue streams for raw materials. The path of consumption in the developing world remains unknown. However, historical analyses suggest that many countries beginning development later will advance quickly and yet saturate at lower levels of consumption. The question remaining is what will be the environmental impacts during the intervening years of unbridled growth.

The demand for better performance, and hence greater sophistication in materials and goods, has lightened many products and is key to future trends in materials consumption and efforts in materials recovery. Research and development efforts will need to combine environmental objectives with consumption trends to reduce primary materials requirements, design products for recovery, and find uses for, so-called, wastes.

Although technology may offer some solutions and help reduce the environmental impact of our consumption, changing human behavior will surely prove more difficult. A great nineteenth century moralist remarked, "The loudest noise in the world is the sound of a person breaking a habit."[1] Technological and economic solutions must recognize the deep behavioral forces driving human consumption to effect positive change. Faced with the choice of asking my young daughter to do without her Barbie doll in an effort to

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[1] Attributed to I. L. Salant, 1810–1883.

help save the planet, or play with a "green" Barbie that minimally impacts the environment, I, and I suspect many readers, choose the latter.

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