

*Mind Over Matter:
Recasting the Role of
Materials in Our Lives*

GARY GARDNER AND
PAYAL SAMPAT

Jane A. Peterson, *Editor*

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Introduction

Imagine a truck delivering to your house each morning all the materials you use in a day, except food and fuel. Piled at the front door are the wood in your newspaper, the chemicals in your shampoo, and the plastic in your grocery bags. Metal in your appliances and your car—just that day's share of those items' total lives—are also included, as is your daily fraction of shared materials, such as the stone and gravel in your office walls and in the streets you stroll. At the base of the pile are materials you never see, including the nitrogen and potash used to grow your food, and the earth and rock under which your metals and minerals were once buried.¹

If you are an average American, this daily delivery would be a burdensome load: at 101 kilos, it is roughly the weight of a large man. But your materials tally has only begun. Tomorrow, another 101 kilos arrive, and the next day, another. By month's end, you have used three tons of material, and over the year, 37 tons. And your 270 million compatriots are doing the same thing, day in and day out. Together, you will consume nearly 10 billion tons of material in a year's time.²

Massive flows like these are a key feature of what has turned out to be a century unique in its use of materials. The scale of materials use by Americans, Europeans, Japanese, and other industrial-country citizens dwarfs that of a century ago—or, for that matter, of any previous era. Consumption of metal, glass, wood, cement, and chemicals in industrial countries since 1900 is unprecedented, having grown some 18-fold in the United States alone.³

From this global river of materials, a stunning array of new products have emerged: skyscrapers, plastic bags, compact discs, contact lenses, ballpoint pens, and spacecraft, to name a few. Most of these products—and most of the world's materials—are consumed in industrial countries: the United States alone uses a third of world materials today. But developing countries are also steering their economies onto materials-intensive development paths. Indeed, the widespread human appetite for all materials has defined this century in much the same way that stone, bronze, and iron characterized previous eras.⁴

These huge flows, however, were not simply expanded versions of the smaller movements of materials that built previous civilizations. While materials have posed dangers to humans throughout history, in this century they were more complex and toxic than ever. Indeed, today's stock of materials draws from all 92 naturally occurring elements in the periodic table, compared with the 20 or so in use at the turn of the century. This larger range of choices enabled scientists to move beyond classic building blocks—wood, ceramics, and metals—as they developed new materials. Advances in polymers, for instance, spurred the development of plastic, a material as common today as wood was at the dawn of the century. And simple materials like silicon—essentially sand, the most common element in the Earth's crust—vaulted from humble building material to the central ingredient in complex products like computer chips. Impressive as they were, improving many aspects of human life, the new materials were also often toxic, and frequently resisted re-absorption into the natural environment at the end of their useful lives.⁵

Because industrial economies were not tooled for recycling, massive materials use in this century also generated huge flows of waste. Waste is as old as settled life, but the scale and toxicity of waste production in modern times is unprecedented. Indeed, by one estimate, the vast majority of materials moving through industrial economies are used only once, then disposed of. This one-time use contrasts

sharply with the practice in earlier eras, when organic materials naturally degraded, and when metal products were used for years before being melted down and transformed into new products. In modern economies, the bulk of waste is invisible to most of us: mining slurry, factory effluent, smokestack emissions, and product trimmings are several times greater in quantity than the garbage collected from our homes and offices.⁶

The massive flows, complex makeup, and unparalleled waste that characterize this materially unique century have also wrought extraordinary damage on human and environmental health. Mining has contaminated more than 19,000 kilometers of rivers and streams in the United States alone, and logging contributes to habitat loss, a primary cause of the mass extinction of species that scientists believe is under way. Air and water pollution from manufacturing plants have sickened millions and threaten many more: one quarter of the Russian population, for example, is exposed to pollution concentrations that exceed health standards by 10 times. Some of the 100,000 synthetic chemicals introduced this century are ticking time bombs, affecting the reproductive systems of animals and humans even a generation after initial exposure. And the effort to make waste disappear—by burying it, burning it, or dumping it in the ocean—has boomeranged, generating greenhouse gases, dioxin, toxic leakage, and other threats to environmental and human health.⁷

This reckless abuse of the natural environment is the product of a “frontier” mindset that views materials, and the Earth's capacity to absorb wastes, as practically limitless. Natural as this perspective may have seemed in the nineteenth century when global population had not yet reached 2 billion, it led to an industrial system that, by hitching progress to materials consumption, became increasingly disruptive. At great expense, and using tremendous quantities of climate-altering fossil fuels, industrial economies destroy natural landscape and habitat to extract raw materials for products such as soda cans and grocery bags, often of little

value, whose useful life may be measured in minutes. Soon, they are discarded in ways that contaminate land, water, or the atmosphere. Then the cycle begins again. Given this record, an extraterrestrial observer might conclude that conversion of raw materials to wastes is a major purpose of human economic activity.⁸

Thoughtful analysis of industrial societies suggests that much of this wasteful activity is unnecessary to provide people with the services and experiences they desire—which makes the current system all the more archaic. If shelter, transportation, education, entertainment, and other human needs can be met with a minimum of materials, especially virgin materials—as innovative new experiments strongly suggest—a new economy, and a new understanding of human development, will emerge. Researchers, policymakers, and firms, especially in Europe, are exploring ways to reduce by 90 percent or more the materials that flow through industrial economies, and thus to substantially lighten the burden that these flows impose on human health and the natural environment. Though much research remains to be done, pioneering efforts to date have yielded impressive results.⁹

The key to reducing materials flows is to abandon frontier economics, which yokes economic activity to materials use. This will require imaginative initiatives and leadership. Re-structuring economies to focus more on the delivery of services and less on the creation of products is one part of the equation. Extending the productive life of products and building them for easy recycling or remanufacture is another part. Linking industries so that the wastes from one factory become the inputs to another offers yet another promising prospect. And persuading consumers of the benefits of consumption habits geared to personal growth, rather than to excess, will be crucial. These far-reaching, even revolutionary initiatives offer a new industrial vision for a new century: bringing economies into harmony with the natural world on which their survival depends.

Constructing a Material Century

The intensive use of materials in this century has deep historical roots. Since the Industrial Revolution, advances in technology and changes in society and in business practices have interacted to build economies that could extract, process, consume, and dispose of tremendous quantities of materials. Although the roots of these trends extend back centuries, most have matured only in the last 100 years.¹⁰

The case of iron, the emblematic material of the Industrial Revolution, illustrates how technological advances fed materials use. In 1879, a British clerk and his chemist cousin invented a process for making high-quality steel—a harder and more durable alloy of iron—from any grade of iron ore, eliminating the need for phosphorus-free ore. This innovation cut steelmaking costs by some 80–90 percent which in turn drove demand skyward: between 1870 and 1913, iron ore production in Britain, Germany, and France multiplied 83-fold. Further innovations and robust demand led to a six-fold increase in world production between 1913 and 1995. Today, iron and steel account for 85 percent of world metals, and a tenth, by weight, of world materials production.¹¹

As richer ores were depleted, new extractive technologies made it possible to mine metal from relatively poor lodes, a practice known as “low-grading.” In 1900, it was not feasible to extract copper, for example, from ore that contained less than 3 percent of the metal. But technological advances have since lowered the extraction threshold to less than 0.5 percent, increasing the number of sites where mining is viable, and greatly expanding the quantity of ore needed to extract the same amount of copper. As world copper production grew 22-fold over the century, in step with rising demand for automotive and electrical uses, waste production grew 73-fold. Likewise, modern logging and mining equipment have made it possible to reduce tracts of forest into sawn lumber in a matter of hours, or to shear off entire

mountaintops in order to reach mineral deposits.¹²

Meanwhile, transportation and energy developments also greased the wheels of the materials boom. With the expansion of roads, canals, railways, and aviation networks, it became easier to haul ever-greater quantities of raw materials to factories and markets. Completion of the Canadian Pacific Railway in 1905, for instance, laid open the country's rich western provinces to mineral exploitation, while locomotives later helped empty Liberian mines of iron ore for European markets. Over the century, the availability of cheap oil—a better-performing fuel than coal or wood—made materials production more economical than ever. The powerful combination of declining costs for energy and raw materials fueled expansion in industrial scale and kept the cycle of exploration and production in constant motion.¹³

Perhaps the most powerful stimulus to materials extraction throughout the century has been the economic incentives that governments offered to materials producers. An 1872 U.S. law, for example—still in effect despite repeated efforts to dislodge it—gives miners title to federal mining land for just \$12 per hectare (\$5 an acre), and charges no fees for metals extracted from these holdings. The title also allows miners to build homes, graze cattle, extract timber, and divert water on this land for no extra fee. During this century, governments in all parts of the world—including Indonesia, Ghana, and Peru—have introduced other incentives, including tax breaks, to attract mining and logging companies. These policies are typically uneconomical: the U.S. government still spends more money on building logging roads than it earns from timber sales.¹⁴

Subsidized access to materials and energy, combined with technological advances, promoted increases in the scale of industry as well as new ways of organizing and managing production. Inspired by the use of standard, interchangeable parts to facilitate large-scale musket production in the early nineteenth century, Henry Ford adopted the concept of mass production in his automobile factories. Ford's moving assembly line and standardized components

slashed production time per chassis from 12.5 hours in 1913 to 1.5 hours in 1914. Costs also fell: a Ford Model T cost \$600 in 1912 but just \$265 in 1923, bringing car ownership within reach of many more consumers. And Ford's total output jumped from 4 million cars in 1920 to 12 million in 1925, accounting for about half of all automobiles made in the world at the time. Soon these mass production principles were adopted by manufacturers of refrigerators, radios, and other consumer goods, with similar results.¹⁵

As the scale of production ballooned, demographic shifts and new business strategies created a market to match it. The U.S. and European labor forces became increasingly urbanized, middle-class, and salaried in the first third of the century, characteristics that facilitated the creation of a consumer class. Material affluence steadily became more accessible to the average individual. Business initiatives encouraged and capitalized on these trends, with Henry Ford once again a leader. In 1914, Ford introduced a daily wage of five dollars—more than twice the going rate—thereby augmenting his workers' spending power. He also reduced working hours, believing, in the words of one analyst, that “an increase in leisure time would support an increase in consumer spending, not least on automobiles and automobile travel.” Other employers loudly opposed shorter workdays but conceded increases in pay for the same reason Ford did: to prime the pump of consumer spending.¹⁶

Prospering workers and their families quickly became the targets of sophisticated marketing efforts. Department stores and mail order catalogs funneled a wealth of goods to the consumer, and consumer credit made those goods affordable: by the end of the 1920s, about 60 percent of cars, radios, and furniture were being purchased on credit. Other clever strategies were used to boost sales too: in the 1920s,

Material savings from “lightweighting” were nearly always offset by increased consumption.

General Motors introduced annual model changes for its cars, playing on consumers' desires for social status and novelty. The strategy succeeded: by 1927, when the industry was still in its infancy, replacement purchases of cars outnumbered first-time purchases. Meanwhile, advertisers used insights from the new field of psychology to ensure that consumers were "never satisfied" (in the words of a DuPont vice-president) and linked the consumer's identity to products. Recognizing the power of advertising to influence purchasing decisions, companies expanded their budgets for promotion. Global advertising expenditure surged over the century, reaching \$435 billion in 1996. As people in developing countries have prospered in recent years, advertising spending there has grown rapidly: by more than 1,000 percent in China between 1986 and 1996, some 600 percent in Indonesia, and over 300 percent in Malaysia and Thailand.¹⁷

Increasingly wealthy industrial nations invested heavily in scientific research, prompting the development of new and versatile materials. Research this century launched plastic into everyday use, boosting its production sixfold since 1960. Early plastics were plant-based, or "celluloid": Henry Ford even "grew" an automobile, making a plastic car body out of straw and other plant matter joined with soy oil. But plastics research was soon reoriented to exploit the unused chemical by-products of fossil fuels. More than 100,000 new chemical compounds have been developed since the 1930s, many of them for use during World War II, boosting synthetic chemicals production 1,000-fold in the last 60 years in the United States alone. Today, these substances form the primary ingredients in chemical pesticides, refrigerants, insulation, and industrial solvents.¹⁸

The military played a role in materials innovation: the B-2 Stealth bomber alone spurred the development of more than 900 new materials. Aluminum smelting, a very energy-intensive practice, was subsidized to produce large quantities of the metal for use in tanks, bombers, and fighter planes during World War II. Its use spread quickly to consumer products after the war, even to low-value household

items like soda cans, boosting aluminum production 3,000-fold in this century. Agricultural chemicals, like wartime hardware, were in part the product of military research and experience. The pesticide DDT was originally used to combat head lice among U.S. troops and to kill malaria-bearing mosquitoes during World War II. Ammonia, the base material for fertilizer, was first produced to supply Germany with explosives during World War I. As a consequence of agricultural researchers' promoting the "Green Revolution" during the 1950s and 1960s, world fertilizer use grew from 14 million tons in 1950 to 129 million in 1996.¹⁹

New materials often replaced traditional ones—plastic frequently supplanted metal, for example—leading to lighter products. But material savings from "lightweighting" were nearly always offset by increased consumption, especially as military suppliers turned their energies to consumer goods after World War II. The share of Japanese households with refrigerators rocketed from 5 to 93 percent in the 1960s, for instance. And global ownership of cars grew 10-fold between 1950 and 1997. Cars are an especially materials-intensive product, consuming a full third of U.S. iron and steel, a fifth of its aluminum, and two thirds of its lead and rubber.²⁰

Automobile use was facilitated by—and spurred—the expansion of roads, houses, and other infrastructure after mid-century. This construction boom prompted an eight-fold increase in global cement production between 1957 and 1995, and a tripling of asphalt output worldwide since 1950. One third of this asphalt was poured into the giant U.S. network of interstate highways. Where this infrastructure supported low- rather than high-density development, as in U.S. suburbs, materials demand shot up, as far more sewers, bridges, building foundations, houses, and telephone cables were needed to service a given number of people.²¹

By the late 1960s, a materials countertrend—recycling—began to develop in step with growing environmental awareness. The practice was not new: strategic materials were recycled during World War II, and organic matter has

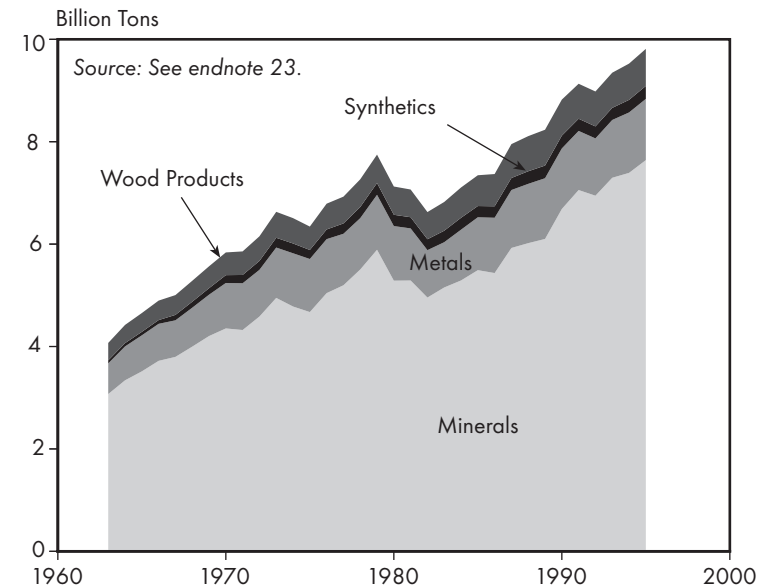
been composted for centuries. But an attempt to root the practice more widely encountered difficulty, because elements of industrial infrastructure, from factory equipment to resource supply lines, had long been tooled to depend on virgin materials, and markets could not easily absorb scrap materials. Despite these deep-rooted obstacles, growth in recycling has been steady: in industrial countries, the share of paper and cardboard recycled grew from an average 30 percent in 1980 to 40 percent by the mid-1990s. Glass recycling levels jumped from less than 20 percent to about 50 percent in the same period. And the share of U.S. metals consumption met by recycling rose from 33 percent in 1970 to almost 50 percent in 1998.²²

Despite the trend in recycling, virgin materials use has continued to rise as the developing world industrializes, and as more affluent nations show no signs of cutting back on consumption. In 1995, nearly 10 billion tons of industrial and construction minerals, metals, wood products, and synthetic materials were extracted or produced globally. This is more than double the level of 1963, the first year for which global data are available for all major categories of materials. (See Figure 1 and Table 1.) (This 10 billion tons does not include hidden flows of material—the billions of tons that never entered the economy but were left at mine sites or smelters. Factoring in these flows, as was done to arrive at the 10 billion tons cited earlier for the United States alone, would at least double and possibly triple the global total materials load.)²³

Production trends in the last half century have varied by material and region. Fossil-fuel-based materials, led by plastics, have grown at more than twice the pace of other major materials categories since 1960, largely because of their light weight, versatility, and low price. Metals have grown at a slower pace, but substantially nonetheless: globally, metals production doubled between 1920 and 1950, and has quadrupled since mid-century. The use of wood products has marched steadily upward since 1961, but in industrial nations, the trend is more complex: wood has

FIGURE 1

World Materials Production, 1963–95



been replaced by other materials for many uses, but paper production has surged.²⁴

Perhaps the greatest variation in materials trends this century is found across regions. The United States was the materials behemoth, towering above all other nations in its appetite for raw materials of all kinds: for example, it has 24 kilometers of road per thousand persons, 9 times more than the Mexican average. Its 18-fold increase in materials consumption since 1900 is globally important in two ways. (See Table 2.) First, the United States has accounted for a dominant share of the world total, 43 percent in 1963, and 30 percent in 1995. Second, its economic and ideological power has made the high-consumption, materials-intensive economic model the desired development path for dozens of countries and billions of people around the world.²⁵

Changing purchasing patterns worldwide reflect this shift. Today, residents of Brazil, Chile, and the Republic of

TABLE 1

Growth in World Materials Production, 1960–95

Material	Production in 1995 ¹ (million tons)	Increase over Early 1960s ² (factor of change)
Minerals ³	7,641	2.5-fold
Metals	1,196	2.1-fold
Wood Products ³	724	2.3-fold
Synthetics ⁴	252	5.6-fold
All Materials	9,813	2.4-fold

¹Marketable production only; does not include hidden flows. ²Minerals and total materials data are for 1963; wood products data are for 1961.

³Nonfuel. ⁴Fossil-fuel-based.

Source: See endnote 23.

Korea buy new television sets at rates comparable to their industrial nation counterparts—about 4 to 6 sets per 100 individuals each year. In China, purchases of refrigerators, washing machines, and television sets shot up 8- to 40-fold between 1981 and 1985—reminiscent of Japan's consumer goods rush in the 1960s.²⁶

On the whole, however, with roughly 20 percent of

TABLE 2

Growth in U.S. Materials Consumption, 1900–95

Material	Consumption in 1995 (million tons)	Increase over 1900 (factor of change)
Minerals ¹	2,410	29-fold
Wood Products ¹	170	3-fold
Metals	132	14-fold
Synthetics ²	131	82-fold
All Materials	2,843	18-fold

¹Nonfuel. ²Fossil-fuel-based.

Source: See endnote 25.

global population, industrial countries still devour far more materials and products—84 percent of the world's paper, and 87 percent of its cars each year—than developing nations do.²⁷

The Shadow Side of Consumption

In the early 1990s, researchers at the University of British Columbia began to calculate the amount of land needed to sustainably supply national populations with resources (including imported ones), and the amount needed to absorb their wastes. They dubbed this combined area the “ecological footprint” of a population. In countries as different as the United States and Mexico, the footprint is larger than the nation's entire land mass, because of a net dependence on imports, or because the area needed to absorb wastes sustainably is larger than the area actually used. Sustaining the whole world at an American or Canadian level of resource use would require the land area of three Earths. Materials use strongly influences the size of a population's footprint: in the U.S. case, materials are conservatively estimated to account for more than a fifth of the total footprint. (Fossil fuel use and food production are other major components.) And other research implicates materials even more heavily. When measured by weight, materials account for 44 percent of the United States' resource use, 58 percent in the case of Japan, and as much as 68 percent in Germany.²⁸

The environmental damage done by materials extraction, processing, and disposal provides more direct evidence that today's materials flows are unsustainable. Demand for wood and paper products—from construction lumber to packaging material to newsprint—continues to strip forests, with serious environmental consequences. Indeed, the World Resources Institute estimates that logging for wood products threatens more than 70 percent of the world's large, untouched forests. And in many parts of the world,

single-species timber plantations have replaced old-growth forests, eroding species diversity, introducing toxic insecticides, and displacing local peoples.²⁹

Healthy forests provide vital ecosystem services, including erosion control, steady supply of water across rainy and dry seasons, and regulation of rainfall. The loss of these services can devastate local watersheds, as China learned in 1998, when deforestation reduced the capacity of hillsides to hold water, leaving the Yangtze River Basin vulnerable to the worst flooding in more than 40 years. Similarly, the massive fires in Southeast Asia in late 1997 and in the Amazon and Central America in 1998 are blamed in part on forest fragmentation, a pattern of forest cutting that exposes forests to drying sunlight and wind.³⁰

Forests also provide habitat to a diverse selection of plant and animal life; tropical forests, for example, are home to more than 50 percent of the world's species. The impact of the loss of these vital ecosystems was underlined in 1998 when a majority of biologists polled in the United States agreed that the world is in the midst of a mass extinction, the first since dinosaurs died out 65 million years ago. The connection between these environmental calamities and the surging demand for wood and paper products—especially in industrial countries—is increasingly difficult to ignore.³¹

Mineral and metals extraction also leaves a lasting and damaging environmental footprint. Mining requires removing from the earth both metal-bearing rock, called ore, and “overburden,” the dirt and rock that covers the ore. Very little of this material is used—for example, on average, some 110 tons of overburden earth and an equal amount of ore are excavated to produce just a ton of copper. (See Table 3.) Not surprisingly, the total quantities of waste generated are enormous: Canada's mining wastes are 58 times greater than its urban refuse. Few newlyweds would guess that their two gold wedding rings were responsible for six tons of waste at a mining site in Nevada or Kyrgyzstan. These mind-boggling movements of material now exceed those caused by natural systems: mining alone strips more of the Earth's surface each

TABLE 3

World Ore and Waste Production for Selected Metals, 1995

Metal	Ore Mined (million tons)	Share of Ore That Becomes Waste ¹ (percent)
Iron	25,503	60
Copper	11,026	99
Gold ²	7,235	99.99
Zinc	1,267	99.95
Lead	1,077	97.5
Aluminum	856	70
Manganese	745	70
Nickel	387	97.5
Tin	195	99
Tungsten	125	99.75

¹ Does not include overburden. ² 1997 data.

Source: See endnote 32.

year than natural erosion by rivers does.³²

Mines use toxic chemicals, including cyanide, mercury, and sulfuric acid, to separate metal from ore. Tailings, the chemical-laced ore that remains once the metal is separated, are often dumped directly into lakes or rivers, with devastating consequences. Tailings from the Ok Tedi mine in Papua New Guinea, for instance, have decimated the fish, crocodiles, crustaceans, and turtles that once thrived in the 70 kilometers of the Ok Tedi River downstream. Moreover, the mining wastes have changed the course of the river, which now floods adjacent farms with poisonous water. And damage to the watershed has disrupted the health and livelihoods of the indigenous Wopkamin people.³³

Toxic meltdowns can occur even when tailings are contained, with the expectation that they will remain intact, instead of being dumped. In 1998, a tailings reservoir in Spain collapsed, spewing 5 million cubic meters of mining sludge onto 2,000 hectares of cropland and killing fish and wildlife in the neighboring Doñana National Park, a World

Heritage Site. Mining is implicated in the contamination of more than 19,000 kilometers of U.S. rivers and streams, some of it virtually permanently. The Iron Mountain mine in northern California continues to leach pollutants into nearby streams and the Sacramento River more than 35 years after its closing. Water downstream of the mine is as much as 10,000 times more acidic than car battery acid. The area is now a “Superfund” site (a high priority for cleanup), but if remediation fails, experts calculate that leaching at present rates will continue for at least 3,000 years before the pollution source is depleted. The U.S.-based Mineral Policy Center estimates that the U.S. government will have to spend \$32–72 billion cleaning up the toxic damage left at thousands of abandoned mines across the country.³⁴

Industrial activity this century has spewed millions of tons of metals into the environment. Global industrial emissions of lead, for example, now exceed natural rates by a factor of 27. The impacts of metals emissions are grave: hundreds of thousands of hectares of Russian forest have been poisoned by emissions from industrial plants; pollution from the Norilsk nickel plant alone has killed 300,000 hectares. Exposure to mercury, which is widely used by miners in the Amazon Basin and West Africa, increases cancer risk and can damage vital organs and nervous systems. And lead, a neurotoxin, stunts children’s cognitive development.³⁵

Resource extraction and processing also degrade the environment indirectly. In the United States, materials processing and manufacturing alone claimed 14 percent of the country’s energy use in 1994. Most of this energy is generated from the burning of fossil fuels, implicating everyday products in global climate change. In addition, cement production contributes about 5 percent of the world’s emissions of carbon, again contributing to climate change.³⁶

This century, modern chemistry introduced new synthetic chemicals, often with unknown consequences, into the remotest corners of the world. In 1995, scientists studying the global reach of organochlorine pesticides reported that almost all of the ones they studied were “ubiquitous on

a global scale.” Other evidence supports this conclusion: researchers looking for a control population of humans free of chemical contamination turned to the native peoples of the Canadian Arctic, only to find that they carried chemical contaminants at higher levels than inhabitants of St. Lawrence, Canada, the original focus of the research. Chemicals had reached the indigenous people through wind, water, and their food supply. Similarly, toxic industrial chemicals were reported found in 1998 in the tissue of whales that feed at great depths in the Atlantic Ocean, in feeding grounds that were presumed to be clean.³⁷

Part of the reason for this worrying development is that many chemicals cannot be recaptured once emitted to the environment. Chlorofluorocarbons (CFCs), for instance, which were long used as refrigerants and solvents, are implicated in the decay of stratospheric ozone. A large share of pesticides used in agriculture—roughly 85–90 percent—never reach their targets, dispersing instead through air, soil, and water and sometimes settling in the fatty tissues of animals and people.³⁸

Many synthetic chemicals are not just ubiquitous but long-lived. Persistent organic pollutants (POPs), including those used in electrical wiring or pesticides, remain active in the environment long after their original purpose is served. Because they are slow to degrade, POPs accumulate in fatty tissues as they are passed up the food chain. Some have been shown to disrupt endocrine and reproductive systems—implicated in miniature genitals in Florida alligators, and abnormally thin bird eggshells, for example—often a generation or more after exposure. The delay in the appearance of health effects caused by POPs raises questions about the wisdom of depending on tens of thousands of newly synthesized chemicals whose effects are poorly understood.³⁹

The long list of unknowns concerning POPs is just a small indication of our chemical ignorance. The U.S. National Academy of Sciences reports that insufficient information exists for even a partial health assessment of 95 percent of chemicals in the environment. If information is lacking on

thousands of individual chemicals, it is almost nonexistent regarding how chemicals interact with each other, or how they work over the long term, or on different segments of the population. And even if this scientific information were available, the actual use of chemicals by industry might remain hidden. In the United States, a database on chemical use by industry known as the Toxic Release Inventory makes public just 7 percent of high-production chemicals, those used at 1 million pounds or more each year.⁴⁰

The dramatic increase since mid-century in another dispersed material, nitrogen fertilizer, along with the increased combustion of fossil fuels, has made humans the planet's leading producers of fixed nitrogen (the form that plants can use), essentially raising the fertility of the planet. But this fertility windfall favors some species at the expense of others. Grasslands in Europe and North America, for instance, are now less biologically diverse because nitrogen deposition has allowed a few varieties—often invasive species—to crowd out many others. And algal blooms resulting from fertilizer runoff in waterways as diverse as the Baltic Sea, the Chesapeake Bay, and the Gulf of Mexico have led to fish and shrimp kills because algae rob other species of the water's limited supply of oxygen. Scientists are just beginning to comprehend the full effects of disrupting the global flow of nitrogen, one of four major elements (along with carbon, sulfur, and phosphorus) that lubricate essential planetary systems.⁴¹

Mountains of materials have been discarded this century, typically in the cheapest way possible in the nearest river or empty field. In a 1991 waste survey of more than 100 nations by the International Maritime Organization, more than 90 percent of responding countries pinpointed uncontrolled dumping of industrial wastes as a problem. Nearly two thirds said that hazardous industrial waste is disposed of at uncontrolled sites, and nearly a quarter reported dumping industrial waste in the oceans. The casual treatment of industrial waste has had terrible environmental, health, and economic consequences in much of the world. One quarter of

the Russian population, for example, reportedly lives in areas where pollution concentrations exceed acceptable limits by 10 times. In the United States, some 40,000 locations have been listed as hazardous waste Superfund sites, and the Environmental Protection Agency estimates that cleanup of just the 1,400 sites of highest priority will cost \$31 billion.⁴²

Finally, municipal solid waste—a relatively small, but high-profile refuse that emanates from homes and businesses—generates its own set of problems. In developing countries, this material is often dumped at sites near cities, sometimes within congested neighborhoods, where it draws rats and other vermin that pose a health threat to nearby residents. In industrial countries, the material is landfilled, incinerated, or dumped in rivers or the ocean, always with environmental consequences. Unless they are lined, for example, landfills often leach acidic juices downward, contaminating groundwater supplies. And rotting organic matter in landfills generates methane, a greenhouse gas with 21 times the global warming potential of carbon dioxide. Methane is sometimes tapped for energy use, but this is not the typical practice. Landfills are responsible for a third of U.S. methane emissions, and a tenth of methane emissions from human sources worldwide.⁴³

Incineration, a common disposal method, also carries a long string of liabilities. Municipal waste incinerators are the single largest source of mercury emissions in the northeastern United States, contributing nearly half of all human-induced emissions in that region. While incineration reduces piles of waste, it also increases emissions of dioxin, a POP, and generally concentrates toxicity in the remaining hazardous waste.⁴⁴

This extensive tally of environmental problems clearly demonstrates that the materials-intensive economic model

Insufficient information exists for even a partial health assessment of 95 percent of chemicals in the environment.

TABLE 4

Hypothetical Increase in Global Materials Use in 1995, Based on U.S. Per Capita Consumption Levels

Material	Increase if World Consumed at U.S. Levels (factor of change)
Minerals ¹	7-fold
Metals	2-fold
Wood Products ¹	5-fold
Synthetics ²	11-fold
All Materials	6-fold

¹Nonfuel. ²Fossil-fuel-based.

Source: See endnote 45.

is unsustainable. And as more countries aggressively apply this model, environmental destruction will only increase. Indeed, if the world's 6 billion people used materials as intensively as the average American, materials use would grow sixfold, and environmental damage would rise at least correspondingly. (See Table 4.) In some cases, the increase in damage could actually outpace the growth in materials use. As the quality of ore grades declines in the 21st century, for example, more waste will be generated per ton of metal mined than was the case 100 years ago. Similarly, as the last habitat in an ecosystem is lost, species extinctions accelerate dramatically. In short, continued heavy use of materials could mean escalating levels of environmental damage in coming decades.⁴⁵

The Limits to Efficiency

The litany of environmental ills associated with intensive materials use led to calls in the early 1990s for a “dematerialization” of industrial economies: a reduction in the materials needed to deliver the services people want. Using

calculations that show global, human-induced flows of materials to be twice as high as natural flows, German researchers recommended in 1993 that global materials flows be cut in half. But they also recognized that most developing countries need to increase materials use just to meet their populations' basic needs. So they concluded that the 50 percent global reduction in materials use would have to be shouldered by the world's heaviest consumers, industrial nations. By the researchers' estimates, this responsibility implies a 90 percent decrease in materials use by industrial nations over the next half century.⁴⁶

This bracing estimate is not meant as a precise prescription for reductions in all types of materials. Some materials, especially toxic ones, may need to be eliminated entirely, while others can be used sustainably at reduction levels short of 90 percent. But the overall estimate is credible enough to be taken seriously by many environmentalists and government officials, especially in Europe. Austria has incorporated a “Factor 10” (90 percent) reduction into its National Environmental Plan, and the Dutch and German governments, along with the Organisation for Economic Co-operation and Development (OECD), have expressed interest in pursuing radical reductions. (See Table 5.) The question is, How can such an ambitious goal be achieved?⁴⁷

Some would argue that materials reductions will occur naturally as economies mature. Once roads, houses, bridges, and other major works of infrastructure are in place, as lighter materials are developed, as recycling programs kick into gear, and as economies sprout more service industries in proportion to factories, this argument runs, a “natural” dematerialization of economies should take place. At first glance, the historical record suggests that this is true, and the trend is now documented for economies globally. Materials intensity—the tonnage of material used to generate a dollar's worth of output—declined by 18 percent between 1970 and 1995, the only period for which global data on materials use has been tracked by the U.S. Geological Survey. The decline occurred without any conscious policy by the

TABLE 5

Recent Proposals for Reductions in Materials Use and For Increases in Materials Efficiency

Group	Year Proposed	Suggested Target ¹	Actions or Proposed Actions
National Level			
Austrian National Environment Plan	1996	10-fold	To be achieved over the next decade.
Swedish Ecocycle Commission	1997	10-fold	Applies to both material and energy efficiency; to be achieved over the next 25 to 50 years.
Dutch National Environment Plan	1997	4-fold	Based on a halving of resource use and a doubling of wealth.
German Environment Ministry	1998	2.5-fold	Applies to non-renewable raw materials; to be achieved by 2020.
International Level			
Factor 10 Club	1994	10-fold	Declaration by 16 eminent scholars from 10 countries; reductions in materials flows to be achieved over 30–50 years in industrial nations.
OECD–Council at Ministerial Level	1996–98	10-fold	Is commissioning studies on the potential for large efficiency gains; views eco-efficiency as highly promising.
U.N. General Assembly	1997	10-fold	Calls for studies; gains to be achieved over 2 to 3 decades.
World Business Council for Sustainable Development and UNEP		10-fold	Calls for improvements in eco-efficiency worldwide.

¹For some groups, target refers to an increase in materials efficiency; for others, it refers to an overall reduction in material use. Increases in efficiency may not result in reduced materials use, especially over time.

Source: See endnote 47.

world's governments to reduce materials use, but reflects instead the maturation of industrial economies, the major users of materials.⁴⁸

Despite the decline in materials intensity, however, total consumption of materials swelled by 67 percent between 1970 and 1995. From an environmental perspective, this absolute level of materials use is the most relevant measure. Beetles and spider monkeys do not care if the trees logged from their forest habitat were pulped into millions instead of thousands of newspapers. From their perspective, the loss of habitat is not cushioned by the increase in materials efficiency. Indeed, decreases in materials intensity, while vitally important, are always insufficient if rising consumption offsets them and encourages continued logging of forests, opening of new mines, and pollution of air and water. In sum, when total materials use jumps—as it has by two thirds since 1970—it is clear that natural dematerialization is far too timid a tool for delivering the 90 percent reduction in total materials use being called for in industrial countries. Clearly, more deliberate actions (discussed in the next section) are needed.⁴⁹

Without a conscious effort to reduce absolute levels of materials use, the gains from natural dematerialization were bound to be modest. Most of the factors that reduced materials intensity—the shift to services, efficiency gains, and increased recycling—were offset or handicapped by other economic or social trends.

Consider, for example, the growing importance of the service sector in many economies. The “products” of the banking, insurance, health, education, and other non-extractive and non-manufacturing industries are less materials intensive than the hard goods emerging from mines, logging operations, and factories. This is why the expansion of service industries is expected to lower materials intensity. But the growing share of the economic pie claimed by service industries does not mean that manufacturing is in decline. The absolute size of the manufacturing sector continues to be substantial, and it continues to generate heavy

flows of materials. Moreover, some services—banking, insurance, or retail, for example—often grease the wheels of firms that devour materials, making these industries instruments of intensive materials use. Finally, service industries, while not heavy producers of materials, can be voracious consumers. Infrastructure services like water, sanitation, transportation, and communications, for example, use huge quantities of materials. Thus, as Asian countries prepare to spend more than 10 trillion dollars on infrastructure over the next three decades, their economies could see a structural shift toward services. But without a conscious materials policy, this shift may not be matched by a reduction in materials use.⁵⁰

Like the shift to a service economy, improvements in materials efficiency gains in recent decades did not dampen overall materials consumption. Technological advances slashed the amount of materials needed for a given use: carbon fibers and other new materials, for example, support about 10 times as much weight today as the same quantity of metal did in 1800. But left to themselves, efficiency gains can often undo real resource savings. And technological complications have prevented efficiency gains from translating into materials reductions across the board. (See Table 6.) Moreover, efficiency gains typically generate economic growth that spurs greater overall consumption of materials. Unless policies are in place to lock in efficiency gains, they can easily unravel under the influence of other technological or economic factors.⁵¹

Meanwhile, recycling, another contributor to declining materials intensity, has only barely been tapped. While global recycling of many metals generally increased in this century, and while recycling of municipal solid waste has jumped rapidly in recent decades, recycling has never been a central feature of most economies. Indeed, recycling is still very much the exception for most materials: more than 73 percent of U.S. municipal solid waste was *not* recycled in 1995, for example. The marginalization of recycling is the result of deep-seated technical and economic obstacles that can only

TABLE 6
Gains in Materials Efficiency of Selected Products and Factors That Undercut Gains

Product	Efficiency Gains	Factors That Undercut Efficiency Gains
Plastics in Cars	Use of plastics in U.S. cars increased by 26 percent between 1980 and 1994, replacing steel in many uses, and reducing car weight by 6 percent.	Cars contain 25 chemically incompatible plastics that, unlike steel, cannot be easily recycled. Thus most plastic in cars winds up in landfills.
Bottles and Cans	Aluminum cans weigh 30 percent less today than they did 20 years ago.	Cans replaced an environmentally superior product—refillable bottles; 95 percent of soda containers were refillable in the United States in 1960.
Lead Batteries	A typical automobile battery used 30 pounds of lead in 1974, but only 20 pounds in 1994—with improved performance.	U.S. domestic battery shipments increased by 76 percent in the same period, more than offsetting the efficiency gains.
Radial Tires	Radial tires are 25 percent lighter and last twice as long as bias-ply tires.	Radial tires are more difficult to retread. Sales of passenger car retreads fell by 52 percent in the United States between 1977 and 1997.
Mobile Phones	Weight of mobile phones was reduced 10-fold between 1991 and 1996.	Subscribers to cellular telephone service jumped more than eightfold in the same period, nearly offsetting the gains from lightweighting. Moreover, the mobile phones did not typically replace older phones, but were additions to a household's phone inventory.

Source: See endnote 51.

be uprooted with a deliberate policy of dematerialization.⁵²

Materials complexity, for example, often deters recycling because of the difficulty of separating materials into their pure, recyclable components. Plastics recycling is hampered by the need to segregate different plastics in order to preserve the desired properties of each. As a result, recycling rates for plastics are typically the lowest of any material in the municipal solid waste stream. Similarly, products made from a mix of materials—from electronic devices containing plastic and metal, to envelopes with plastic windows—are expensive to recycle because of the work required to disassemble them. Such problems are surmountable, by designing products with recycling in mind, for example, or by taxing virgin materials to make the processing of scrap material economically viable. But because absolute reduction in materials use was not a policy priority in the past three decades, creative options like these were not pursued.⁵³

Recycling is also hampered when materials are dissipated during use because these materials are difficult to recover. While dissipated material accounts for only a small share of material flows through most economies, it is often hazardous material that threatens environmental and human health—chlorofluorocarbons, for example. Dissipated material is thus a high priority for recycling if it is recoverable. Alternatively, it may need to be eliminated entirely. Indeed, the impossibility of recycling dissipated lead, and the hazards associated with the material, prompted the United States to outlaw lead use in paint and gasoline in the 1970s, a move that was followed by a noticeable drop in the blood lead levels of the U.S. population. And banning dissipative use caused the recycling rate of other forms of lead to jump dramatically. The United States has nearly closed the loop on lead flows: it now recycles lead at a rate of 93–98 percent. But lead is the exception. Again, lack of policies to reduce absolute levels of materials use, especially the levels of dangerous materials, allows dissipative materials use to continue.⁵⁴

At a broader level, markets for secondary materials are often plagued by the limited capacity of most economies to

absorb them. Economies tooled to use virgin materials will naturally find the demand for secondary materials limited. In Canada, for example, taxes are shifted away from virgin materials producers and away from disposal—and shifted onto recyclers. Indeed, tax rates for recycled material are on average 27 percent compared to 24 percent for virgin material, resulting in a \$367 million (Canadian) disadvantage to the recycling industry. Unless the structural biases against recycling are uprooted, expanding recycling programs simply worsens the glut of secondary material and depresses prices further.⁵⁵

In short, recycling as currently structured focuses on materials that are easily collected, and easily stripped of foreign matter, and for which a market exists. As long as little effort is made to loosen these parameters, recycling will remain a marginal activity. Some analysts, for example, believe that recycling rates for municipal solid waste under current market conditions and regulations will bump into an upper limit of about 40 percent (compared to the 1995 rate of 27 percent for municipal garbage in the United States). In cases where higher rates have been achieved, credit is usually given to a changed set of regulations or prices that begin to boost recycling. The Institute for Local Self-Reliance in Washington, D.C., documents how modest changes in incentives helped 17 communities to achieve recycling rates ranging from 40 to 65 percent. Greater changes in incentives, applied even beyond urban waste to more substantial waste flows, have the potential to reduce wastes dramatically.⁵⁶

In sum, major reductions in materials use were not achieved over the past several decades, mainly because there was no intent to do so. The shift to a services-dominated economy was driven by economic factors, not by a desire to reduce materials use. Increases in materials efficiency, especially lightweighting, were also propelled by economics, as

More than 73 percent of U.S. municipal solid waste was *not* recycled in 1995.

well as by consumer preferences. Recycling was motivated by a desire to reduce waste, and was largely limited in scope to “end-of-the-pipe” initiatives. And in any case, the inadvertent gains achieved were undone by ever-escalating levels of consumption.

Even now, as materials efficiency is gaining greater attention, the vision of potential materials reduction is often inadequate. The OECD estimates, for example, that under current market conditions and environmental policies—that is, without a transformation of the materials system—firms in industrial nations can make profitable reductions in materials (and energy) use of 10 to 40 percent. They cite a study of 150 businesses in Poland, for example, showing that waste could be reduced by 30 percent just from equipment modernization. Such reductions are worthy of encouragement, but they fall short of the materials cuts of 90 percent that are increasingly advocated. Indeed, the 10–40 percent potential reductions identified by the OECD may be farther from the ambitious reduction goals than the math implies, since early efficiency gains are typically far easier to achieve than later ones. Only changes to materials-consuming systems can complete the materials reduction job.⁵⁷

Remaking the Material World

A true materials makeover will require a rethinking of the structure and purpose of modern economies. Expectations of services, recycling, and efficiency will need to be completely overhauled, with low materials “throughput” (from extraction to use to waste) as a primary goal. Businesses will need to focus more on providing services, and less on producing goods. Recycling will need to be recast from an end-of-the-pipe waste solution to a front-end savings decision. Gains in materials and production efficiency will need to be monumental rather than incremental, as they have been. And consumers will need to critically assess

their consumption choices, drawing the line when purchasing patterns threaten to lower their quality of life. Whether such changes can lead to the ambitious materials reductions now being called for in Europe and other regions has not been proven. But the experience of several industries and economies that have rethought the role of materials from the ground up suggests that dramatic savings are possible.

Achieving major materials reductions would require decoupling materials use from economic growth. Analyst Walter Stahel of the Product Life Institute in Geneva calls the resulting economy a “lake” economy, in which a stock of material circulates indefinitely; this contrasts with today’s “river” economies, through which materials flow in one direction. The shift toward a lake economy will require producers to look beyond their factories and think imaginatively about how to deliver what consumers want without using much material. (See Table 7.)⁵⁸

Perhaps the most revolutionary shift on the path to sustainable materials use is the conversion of manufacturing firms to service-providing firms (as distinct from today’s service industries). Service providers earn their profits not by selling goods, such as washing machines or cars, but by providing the services that goods currently deliver—convenient cleaning of clothes, for example, or transportation. They would also be responsible for all the materials and products used to provide their service, maintaining those goods and taking them back at the end of their useful lives. Service firms would thus have a strong incentive to make products that last, and that are easily dismantled, repaired, upgraded, and reused or recycled.⁵⁹

In effect, many service-provider firms would become lessors rather than sellers of products. The Xerox Corporation is a widely cited example. The company now leases most of its office copy machines as part of a redefined mission to provide document services, rather than to sell photocopiers. This arrangement has given the company a strong incentive to maximize the life of its machines: between 1992 and 1997 Xerox doubled the share of copiers that are

TABLE 7
Opportunities to Revolutionize the Materials Economy

Strategy	As Practiced	Potential
Recycling	"Clean residuals" (easily recoverable and uncontaminated scrap) recycled.	Recycling integrated into every stage of the economy, covering all wastes and products.
Efficiency	Defined as material use per unit of <i>output</i> , and measured only at the factory gate.	Defined as material used per unit of <i>utility</i> , and measured over the life of the product or material.
Substitution	Advanced materials derived from non-renewable fossil fuel feedstocks.	Advanced materials derived from renewable plant feedstocks, with an emphasis on reducing toxicity.
Services	Limited to industries outside of mining, agriculture, and manufacturing. Not necessarily "materials-light."	Recasts firms from any sector as service providers. Strong incentive to reduce materials intensity.
Sufficiency	Largely ignored.	Consumers develop criteria for "enough" consumption, based on their assessment of real needs.

Source: Worldwatch Institute.

remanufactured—to 28 percent—a strategy it says saved 30,000 tons from landfills in 1997 alone. Each remanufactured machine meets the same standards, and carries the same warranty, as a newly minted one. In addition, Xerox introduced a product-return program for spent copy and printer cartridges in 1991, and now recaptures 65 percent of used cartridges. As the company adopts other innovative strategies to conserve materials and reduce waste, it expects to boost the remanufactured share of its machines to 84 per-

cent, and the recycled share of its material to 97 percent.⁶⁰

Similarly, Interface, the world's largest carpet tile manufacturer, aims to become a carpet service provider by accepting full, lifelong responsibility for its carpets. Whereas the company once scrambled to sell as much carpet as possible, moving tons of non-recyclable carpet fibers, glues, and backing through the economy each year, it has worked since 1994 to conserve and reuse materials to the maximum extent possible. The company leases its carpet tiles to offices, replacing only the worn tiles as needed. This strategy, combined with the use of recyclable carpet fibers (which Interface is working to perfect), can substantially reduce the company's need for virgin materials and its output of waste. Already, Interface reports encouraging results: a 25 percent increase in sales between 1995 and 1996 was achieved with virtually no increase in raw materials use. And landfilled factory wastes have dropped by 60 percent since 1995, saving the company \$67 million.⁶¹

Some services would save on materials by eliminating goods that spend most of their time idle. One study estimates that over a set period, the use of laundry services rather than home washing machines could dramatically cut materials use per wash, because semi-commercial machines are used more intensively than home washers are. Indeed, home washers are 10 to 80 times more materials intensive—depending on how they are disposed of—than the machines used in a laundromat. If dismantled and recycled, a home washer uses 10 times as much material per wash as a semi-commercial machine that is disposed of in the same way. But if the household machine is landfilled and the semi-commercial machine is recycled, the difference in materials intensity jumps to 80-fold, in favor of the laundromat machine. The example illustrates the gains that are possible by rethinking materials use from the earliest stages, in contrast to the present focus on end-of-pipe solutions such as recycling or waste clean-up.⁶²

Washing may be a function that consumers would prefer to retain in their homes, but even home washing could

be accommodated by a service firm if the machines were leased. This option would save less material than the use of a laundromat, but much more than if machines are bought by individuals. In sum, whether service is provided directly (by hiring someone to mow your lawn, for example) or indirectly (by leasing a lawnmower), replacing infrequently used goods with services can save substantial tonnages of material.

To an extent, service providers replace some materials with intelligence or labor. As the computer revolution continues to unfold, digital technology—basically embodied intelligence—can be used to breathe new life into products such as cameras and televisions that rapidly become obsolete. If product capabilities are upgraded through the replacement of a computer chip, perfectly good casings, lenses, picture tubes, and other components can avoid a premature trip to the landfill. Similarly, labor can be used to extend the useful life of products: service providers need workers to disassemble, repair, and rebuild their leasable goods, saving materials and increasing employment at the same time.

Some questions may need to be resolved before switching to a service economy, however. There may be unanticipated social effects. What happens to low-income people, for example, when the supply of secondhand products dries up as more and more sofas, carpets, and refrigerators are leased? A service economy could deprive them of a key survival strategy, forcing them to pay monthly lease rates or eliminating their durable goods use altogether. But the subsidies that now aid powerful materials producers—fueling wasteful materials use—might instead finance access to essential services. Another concern is that product leasing might edge out smaller firms in favor of those that vertically integrate product design, manufacture, and repair. Forestalling these inequities is a challenge for societies making the leap to a service economy.⁶³

The gains from a revolutionized service economy can be augmented by an equally ambitious overhaul of recycling

practices. This is already starting to happen as products are designed with recycling in mind. Computer cases, for instance, are increasingly made with single materials, and some use no glues, paints, or composites that might impede recycling. German auto-makers now bar-code car components to identify to scrap dealers the mix of materials contained in each piece. And some producers of cars, television sets, and washing machines build their products for easy disassembly at the end of the product's life. Easy disassembly can bring substantial gains. Xerox's ambitious plan to boost the share of remanufactured machines from the current 28 percent to 84 percent, for example, is feasible because of the company's 1997 shift to redesigned, easily disassembled copy machines. Widespread adoption of these "design-for-environment" initiatives could boost recycling rates throughout the economy, and there is much room for improvement: today, just 17 percent of durable goods are recycled in the United States.⁶⁴

With the right incentives, even greater materials reductions from recycling are possible. Germany adopted a revolutionary package waste ordinance that went into effect in 1993 which holds producers accountable for nearly all the packaging material they generate. The new law dramatically increased the rate of packaging recycling, from 12 percent in 1992 to 86 percent in 1997. Plastic collections, for example, jumped nearly 19-fold, from 30,000 tons in 1991 to 567,000 tons in 1997. Better yet, the law gave producers a strong incentive to cut their use of packaging, which dropped 17 percent for households and small businesses between 1991 and 1997. Use of secondary packaging—outer containers like the box around a tube of toothpaste—has especially declined. Several countries, including Austria, France, and Belgium, have adopted legislation similar to Germany's.⁶⁵

Other creative initiatives could expand recycling at the factory level. A network of industries in Kalundborg, Denmark, has championed the concept of industrial symbiosis, under which discharges unusable in one factory become inputs to other factories. Warm water from Kalundborg's

power plant is used by a nearby fish farm, sludge from the fish farm fertilizes farmland, and fly ash from the power plant is used to make cement. The scheme saves the firms millions of kroner in raw materials costs, and diverts, annually, more than 1.3 million tons of waste from landfills or ocean dumping, as well as some 135,000 tons of carbon and sulfur from emission to the atmosphere. Encouragingly, the concept is not limited to the industrial world. A similar setup in Fiji links together a brewery, a mushroom farm, a chicken-raising operation, fish ponds, hydroponic gardens, and a methane gas production unit, all small in scale. Other zero-waste efforts are under way in places as diverse as Namibia and North Carolina.⁶⁶

Given the environmental and financial advantages of industrial symbiosis, the wonder is that such projects have not proliferated naturally. Several obstacles, including awkward distances between complementary industries, lack of information about waste availability, and regulations that prohibit waste reuse, have prevented widespread adoption of these industrial parks. At Kalundborg, these obstacles were minimized: the scheme evolved over 25 years, which facilitated the addition of complementary industries; the small town's strong community ties enabled industry leaders to communicate with each other about available waste; and the relatively high degree of sensitivity to environmental matters in Denmark spurred interest in addressing waste issues. Alternatively, such complexes can be planned, as in Fiji, to ensure that the right partners find each other. Because industrial nations may find it difficult to link far-flung, established industries, the greatest short-term potential for industrial symbiosis may be in countries or regions that have not yet begun to industrialize.⁶⁷

As with service firms and recycling, materials efficiency can be imaginatively rethought and powerfully upgraded. If the efficiency of a product were measured not just at the factory gate—in terms of the materials required to produce it—but across its entire life, characteristics such as durability and capacity for reuse would suddenly become important. For

example, doubling the useful life of a car may involve no improvement in materials efficiency at the factory, but it cuts in half both the resources used and the waste generated per trip over the car's life—a clear increase in total resource efficiency. Recognizing these benefits, many companies are emphasizing the durability of the products they use. Toyota, for example, shifted to entirely reusable shipping containers in 1991, each with a potential lifetime of 20 years. Advances like these, expanded to the entire economy, would sharply reduce container and packaging waste—which account for some 30 percent of inflows to U.S. landfills.⁶⁸

Product life is also extended through the remanufacture, repair, and reuse of spent goods. The environmental impact of beverage consumption in Denmark has fallen considerably since the country switched from aluminum cans to glass containers that can be reused between 50 and 100 times. Widespread adoption of these measures would in some ways be a step back to the future. Most grandparents in industrial countries can remember an economy in which milk bottles and other beverage containers were washed and reused, shoes were resoled and clothes mended, and machines were rebuilt. Some may remember that all but two of the U.S. ships sunk at Pearl Harbor were recovered, overhauled, and recommissioned, in part because of the savings in time and material that this option offered. That such practices seem strange to new generations of consumers is a reflection of how far industrial economies have drifted from the careful use of material resources.⁶⁹

Extending product life offers an array of advantages over the habitual use of virgin materials and the manufacturing of new products. For starters, fewer wastes are generated when products spend more time circulating through an economy. But less apparent gains are at least as important. Reducing logging and mining would save gargantuan amounts of energy: materials extraction and processing account for an estimated 75 percent of the energy used by industry in some industrial countries. In addition, extending product life adds value to old materials and is a rich

source of job creation. In 1996, the remanufacturing industry in the United States employed 10 times as many workers as metals mining did, and earned \$53 billion—a sum greater than the sales of the entire consumer durables industry.⁷⁰

A shift to remanufacturing could revitalize local industry and employment because centers for repair and rebuilding would be most economical as regional, rather than global, activities. However, in industrial nations, labor costs make repair and remanufacturing expensive; an economy-wide shift to repair and remanufacturing would probably require changes at the political level, such as a realignment of the relative costs of capital and labor through tax-shifting.⁷¹

Materials substitution can be elevated several notches by introducing strict environmental criteria into substitution strategies. Because the use of nonrenewable materials—especially petrochemicals—is ultimately unsustainable, some analysts maintain that they should be replaced with biomass-based materials, shifting economies from a “hydrocarbon” base to a “carbohydrate” one. Biodegradable materials made from plant starches, oils, and enzymes can replace synthetics and eliminate toxic impacts. These materials are now used in products as diverse as paints, adhesives, dyes, and microsurgical implements. Enzymes have replaced phosphates in 90 percent of all detergents in Europe and Japan, and in half of those in the United States. Vegetable oils can replace mineral oils in paints and inks: three out of four American daily newspapers now use soy-based, biodegradable inks. And starch or sugar can substitute for petroleum in plastics.⁷²

Questions remain about the feasibility of such a shift, however. With cropland and forests already threatened by urban and industrial expansion, scarcity of land for industrial crops could prevent a large-scale shift to carbohydrate-based materials. Some analysts argue that agricultural and pulping wastes can provide sufficient feedstocks to displace petrochemical-based materials. Others counter that the natural place for agricultural waste is in soils, where they improve soil health by boosting the level of nutrients and

organic matter. And biomass may be cultivated using questionable inputs, including synthetic pesticides, petroleum-fueled equipment, and genetically modified seeds. These concerns aside, plant-based materials could substantially reduce many of the environmental and health hazards associated with petroleum-based materials.⁷³

Finally, while reducing consumption can save resources, it has other benefits as well. Societal ailments ranging from excessive consumer debt to spiritual vapidness and weakened community ties are often blamed on an excessive preoccupation with purchases. And it matters little whether the focus of the shopping is a good or a service. Indeed, a service economy and an insatiable consumer society could easily coexist. For a service economy to actually lead to substantial reductions in materials use, individuals will likely have to learn to limit their consumption to levels that are healthy for the environment as well as for society and themselves.⁷⁴

Thus, consumers need to be involved if real reductions in materials use are to occur. One idea that could at once limit materials consumption, build community, save money, and meet people’s needs is to promote the sharing and borrowing of goods. Car-sharing operations in Berlin, Vancouver, and other cities make cars available to people who do not own an automobile. Participants rely on public transportation, cycling, or walking for most of their transportation needs, but use a car from their co-op for special trips. In Switzerland, where car-sharing has grown exponentially over the last 10 years, thousands have given up their cars and now drive less than half the annual distance they did before the switch. These individuals report an improved quality of life and greater flexibility in personal mobility, without the stress of car ownership. Meeting the full market potential of car-sharing under existing transportation and economic conditions would eliminate an estimated 6 mil-

A shift to remanufacturing could revitalize local industry and employment.

lion cars from European cities.⁷⁵

Another imaginative sharing initiative is the “tool libraries” sponsored by the cities of Berkeley, California, and Takoma Park, Maryland, in the United States. Participants have access to a wide range of power and hand tools—a materials-light alternative to owning that makes sense for people who use tools only occasionally.⁷⁶

At the individual level, the use of neighborhood bulletin boards or web pages could promote sharing of goods. Some 350 local trading networks in the United Kingdom have facilitated such efforts, with members creatively bartering goods and services—lending a video recorder or computer, for example, in return for bicycle repair assistance or a haircut. Another creative initiative is the California-based on-line auction house known as e Bay, through which individuals can post items for sale. Started in 1995, this virtual marketplace does more business than many on-line retailers, much of it in secondhand goods.⁷⁷

Shifting Gears

Overhauling materials practices will require policies that steer economies away from forests, mines, and petroleum stocks as the primary source of materials, and away from landfills and incinerators as cheap disposal options. Businesses and consumers need to be encouraged to use far less virgin material and to tap the rich flow of currently wasted resources through product reuse, remanufacturing, or sharing, or through materials recycling.

A key policy step in this direction is the abandonment of subsidies that make virgin materials seem cheap. Whether in the form of direct payments or as resource giveaways, assistance to mining and logging firms makes virgin materials artificially attractive to manufacturers. The notorious 1872 Mining Law in the United States, for instance, continues to give mining firms access to public lands for just \$12

per hectare, without requiring payment of royalties or even the cleanup of mining sites. The effect of this virtual giveaway is to encourage virgin materials use at the expense of alternatives such as recycling. By closing the subsidy spigot for extractive activities, policymakers can earn double dividends. The environmental gains would be substantial, because most materials-driven environmental damage occurs at the extractive stage. And the public treasury would be fattened through the elimination of tax breaks or other treasury-draining subsidies, and possibly through payments from the mining and logging operations that remain open. What’s more, these benefits would be achieved at little social cost: mining and logging, for example, provide few jobs. In the United States, metals mining employed 52,000 workers in 1996, just 0.04 percent of its workforce that year. Moreover, many of these jobs are already threatened by a trend towards automation in the extractive industries.⁷⁸

Like virgin materials extraction, waste generation can also be substantially curtailed, even to the point of near-zero waste in some industries and cities. A handful of firms report achieving near-zero waste levels at some facilities. The city of Canberra, Australia, is pursuing a “No-Waste-by-2010” strategy. And the Netherlands has set a national waste reduction goal of 70–90 percent. A key instrument for meeting such ambitious targets is taxation of waste in all its forms, from smokestack emissions to landfilled solids. Pollution taxes in the Netherlands, for example, were primarily responsible for a 72–99 percent reduction in heavy metals discharges into waterways between 1976 and the mid-1990s. High landfill taxes in Denmark have boosted construction debris reuse from 12 to 82 percent in eight years—head and shoulders above the 4 percent rates seen in most industrial countries. Such a tax could bring huge materials savings in the United States, where construction materials use between 2000 and 2020 is projected to exceed total use in the 20th century.⁷⁹

At the consumer level, a waste tax can take the form of higher rates for garbage collection or, better still, fees that

are based on the amount of garbage generated. Cities that have shifted to such a system have seen a substantial reduction in waste generation. “Pay-as-you-throw” programs in which people are charged by the bag or by volume of trash illustrate the direct effect of taxes on waste. Dover, New Hampshire, and Crockett, Texas, for instance, reduced household waste by about 25 percent in five years once such programs were introduced. These initiatives are most effective when coupled with curbside recycling programs: as disposal is taxed, people recycle more. Eleven of 17 U.S. communities with record-setting recycling rates have pay-as-you-throw systems.⁸⁰

A modified version of a waste tax is the refundable deposit—essentially a temporary tax that is returned to the payer when the taxed material is brought back. High deposits for refillable glass bottles in Denmark have yielded huge paybacks: return rates are around 98–99 percent, implying that bottles could be reused 50–100 times.⁸¹

Some waste is so harmful or difficult to track that regulation, rather than taxes, may be needed to ensure that it is controlled. The outlawing in the United States of lead emissions, which were found to damage the intellectual development of children, is a case in point. Likewise, the international phaseout of ozone-depleting substances has reduced their use substantially—by 88 percent in the case of chlorofluorocarbons, chemicals that were commonplace in refrigerators and air conditioners just a few years ago. And under negotiation is an international phaseout of 12 chlorinated compounds, including the pesticide DDT, and dioxin, a byproduct of incineration. Where the human and environmental costs of using particular materials is too high, a ban may be the only way to reduce the threat they pose.⁸²

As economic brakes are applied to extraction, waste disposal, and toxic emissions, the incentives to shift to new modes of production and consumption become more attractive. But other government initiatives can facilitate the shift as well. If producers, for example, were made legally responsible for the materials they use over the entire life of those

materials, they would have a strong incentive to cut usage to a minimum and to make the materials they continue to use durable and recyclable. Some 28 countries have implemented “take-back” laws for packaging materials, 16 have done so for batteries, and 12 are planning similar policies for electronics. The best documented of these measures is the 1991 German packaging ordinance. Not only did it lead to substantial cuts in packaging, it also prompted the production of long-lasting products. The International Fruit Container Organization, born out of the 1991 law, became the leading manufacturer and lessor of reusable shipping crates, which now carry 75 percent of all produce shipped through Germany. Extending the concept of producer responsibility throughout the economy could have a profound effect on materials use.⁸³

Recycling would also be facilitated by removing policies that discriminate against it. In Canada, a slew of fiscal policies such as higher taxes on inputs to recycling, for instance, and write-offs for the depreciation of new mines tilt the playing field against recyclers. Eliminating such policy biases would allow recycling to compete on more even terms.⁸⁴

Governments can also boost recycling by setting higher targets for recycled content in products. This would ease the pressure on virgin material sources, and would also raise the value of recycled materials. In the United Kingdom, the world’s fifth highest paper consumer, a bill under debate would increase the recycled content of newspapers from 40 to 80 percent. And by making wood panels with a 70 percent recycled content, the United Kingdom could reduce primary wood use in panels by up to 20 percent.⁸⁵

Building codes can also be revised to permit the use of recycled material in construction. Out-of-date building codes often stipulate the use of particular materials for a job rather than specifying a particular standard of performance.

Landfill taxes in Denmark have boosted construction debris reuse from 12 to 82 percent.

Innovations such as drainage pipes made of recycled plastic are not widely adopted in the United States, for example, often because safety and performance standards for their use have not been set. Revision of these codes—after adequate testing to ensure safety—could open the door to safe and extensive use of recycled building materials and alternative building methods.⁸⁶

Waste exchanges—information centers that help to match suppliers of waste material with buyers—can be promoted as a way to reuse a diverse set of materials. Authorities in Canberra have set up a regional resource exchange on the Internet as part of their campaign to eliminate waste by 2010. The government encourages local businesses to use the exchange, which handles material as diverse as organic waste and cardboard boxes. A private sector initiative in the border region centering on Matamoros, Mexico, and Brownsville, Texas, is even more ambitious. It uses a computer model to analyze the waste flows and material needs of hundreds of businesses in the region, identifying potential supply matches that businesses were unaware of.⁸⁷

To determine targets for materials reductions, policymakers will need a clear understanding of the quantities of materials that flow through their economies, and of the maximum levels of materials use that are sustainable. Materials accounting studies are needed that can give a detailed picture of materials flows by type and by industry. In a few countries, this work has begun. But the analysis needs to be done for all countries, and at a greater level of detail. Equally challenging will be developing yardsticks for sustainable limits of materials use. The ecological footprint analysis developed at the University of British Columbia is a step in this direction. Only by understanding overall flows, and determining whether they are sustainable, can national materials use be critically assessed.

Analysis of overall flows may demonstrate that changes in production were not enough to reduce materials use to sustainable levels. In this case, changes in consumption may be required. Interestingly, new research questions the very

purpose of materials consumption. A new study from the University of Surrey in the United Kingdom indicates that between 1954 and 1994, British consumers attempted to fulfill nonmaterial needs, such as affection, identity, participation, and creativity, with material goods—despite little evidence that this is possible. This questionable consumption pattern thus represents a grossly inefficient use of resources. Civic entities—from religious groups to environmental organizations—are well suited to articulate the social and environmental costs of these excesses.⁸⁸

Community and neighborhood-based organizations can help develop strategies for reducing materials consumption. One particularly successful approach is the Eco-Team Program of the international organization Global Action Plan for the Earth (GAP). More than 8,000 neighborhood teams in Europe and 3,000 in the United States, each consisting of five or six households, meet regularly to discuss ways to reduce waste, use less water and energy, and buy “green” products. GAP reports that households completing the program have reduced landfilled waste by 42 percent, water use by 25 percent, carbon emissions by 16 percent, and fuel for transportation by 15 percent. They also report annual savings of \$401 per household.⁸⁹

Religious groups might reflect on the relationship between excessive consumption and the modern decline in spiritual health. They are well positioned to warn of the dangers of making goods into gods, and their influence in many societies is tremendous. They are also qualified to deliver the positive side of the consumption message: that healthy consumption—moderation in purchasing, with an emphasis on goods and services that foster a person’s growth—feeds the spirit and helps people achieve their fullest potential.

In addition to these changes in policies and behaviors—each of which could have an immediate effect on materials use—policymakers need to pay close attention to the consequences of other decisions with indirect yet profound materials impacts. Indeed, these societal choices—from the way land is used to the price of energy, labor, and

materials—can affect levels of materials use for decades.

Consider, for example, the question of land use. The gangly suburbs of the United States use more kilometers of pavement; more sewer, water, and telephone lines; and more schools and police and fire stations to service a given population than if development patterns were denser. The Center for Neighborhood Technology in Chicago recently studied seven counties surrounding Chicago and found that low-density development was about 2.5 times more materials intensive per inhabitant than high-density development.⁹⁰

While the vast openness around many U.S. cities makes sprawl possible, it is political choices that activate this pattern of resource-intensive development. Zoning laws, for instance, encourage low-density development. And, fossil fuel subsidies make petroleum-based construction products—from asphalt to plastic water lines—artificially cheap. More than \$100 billion in subsidies mask the true cost of driving in the United States, reducing a natural disincentive to live far from work and other important destinations. The full materials implications of these political decisions and subsidies extend well beyond heavy infrastructure demands: distant residential development often makes two cars per household a necessity, while large homes and yards encourage the purchase of more goods to fill them.⁹¹

Most urban planners, zoning officials, and politicians are unaware of the full impact of their land-use decisions on materials use and on the environment. But this is just one of many areas of political decisionmaking that heavily influence levels of materials use. The relative prices of labor and capital are also important. Key elements of a sustainable materials economy, such as sorting recyclable material and disassembling products for recycling, are often labor intensive and therefore prohibitively expensive in an economy based on high wages and cheap raw materials. In a 1998 survey of U.S. consumers, for example, half of those who threw out appliances cited the high cost of repair and a third cited the low cost of replacement as principal reasons behind their decision to junk the goods.⁹²

Other grand policy choices also have far-reaching effects: it is materially relevant, for example, whether a society chooses cars or a bicycle/rail combination as the foundation of its transportation system. Energy pricing matters too, as cheap energy extends the material base of nearly everything in the economy. And some analysts worry that workers' limited freedom to choose shorter working hours over pay increases fosters a "work-and-spend" cycle that boosts materials use. Indeed, most economic activities have profound materials consequences.⁹³

Recognizing the problems caused by depending on materials is a first step in making the leap to a rational, sustainable materials economy. Once this is grasped, the opportunities to dematerialize our economies are well within reach. Societies that learn to shed their attachment to things and to focus instead on delivering what people actually need might be remembered 100 years from now as creators of the most durable civilization in history.

Notes

1. This paper looks exclusively at non-fuel and non-food materials including minerals, metals, wood-based products, and fossil-fuel-based synthetic substances such as plastics and asphalt (referred to collectively as “synthetics” in this paper).
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