Pergamon

Technology In Society, Vol. 16, No. 2, pp. 139–154, 1994

0160-791X/94 $6.00 + .00

0160-791X(94)E0005-W

Directions for Environmental Technologies

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ABSTRACT. Over the long term, Green Evolution will occur because sociotechnical systems advance a few percent per year along environmentally desirable directions or trajectories. Burning carbon and heavy use of materials create many environmental concerns. Thus, critical directions include decarbonization and dematerialization. Decarbonization, which is well established, is the decline in tons of carbon used to generate a particular amount of energy. Dematerialization is the decline in the intensity of materials used to produce particular economic goods. Together, decarbonization and dematerialization can key a superior industry ecology, an economically more efficient and environmentally less harmful network of industrial processes. Annual corporate environmental audits might move the system more rapidly and steadily in the favored directions.

Introduction

Environmental technologies should preserve and spare resources, remedy environmental damage, and lessen and prevent pollution. But how do we recognize the green technologies around us? What are important criteria for new ones? And how do environmental technologies relate to other concerns such as job creation, trade and international relations, and the adequacy of governmental institutions?

This paper seeks to provide orientation for environmental technologies, the tools for a long-term Green Evolution. Accomplishing this orientation involves three concepts: industrial ecology, decarbonization, and

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dematerialization. Industrial ecology provides the framework for recognizing environmental technologies. Decarbonization and dematerialization are important trajectories of environmental performance. A superior industrial ecology characterized by decarbonization and dematerialization sets the key directions for the United States and other countries to develop and apply new technologies.

Industrial Ecology

Industrial ecology is the totality or the pattern of relationships between different industrial activities, their products, and the environment.[1,2] Analytically, industrial ecology is the network of all industrial processes as they may interact with each other and live off each other, economically and also in the sense of direct use of each other's material and energy wastes.

All living matter is a system for the transformation of materials and energy. If we think of ecosystems absent human activity, these systems cycle materials quite completely. Almost everything that is an output of one process feeds another. The concept of waste or garbage means little in the green world. This was not the case when life began. Billions of years of evolution have wrought complex, reproductive chains for food, energy, and materials.[3]

The industrial economy is also a system for the transformation of materials and energy. Our present industrial ecosystem resembles the early stages of biological evolution. The organisms of ancient aeons obtained their energy from a stock of organic molecules accumulated during times before life began. Processes went "once-through" rather than looped.

Industrial ecology aims for a more elegant, less wasteful network of industrial processes. In social terms, it should offer the possibility of superior efficiency and productivity in serving human needs with reduced environmental impact, reduced consumption of raw materials, and inclusion of wastes and products at the end of their lives in the industrial food web as both material and energy.

Vast improvements are possible. The thermodynamic (2nd law) efficiency of energy use in the United States is abysmal: to employ 1 unit of energy productively for the end-user, we mobilize about 20 at the outset. Though more elusive to measure, materials use is certainly also clumsy.

History demonstrates the remarkable capacity of societies to learn to produce goods and services better. However, in setting goals, we must also recognize that the rate for improving economic functions sustained over decades usually averages only a few percent per year.[4] The enormous distance between today's technologies and those of 50 or 100 years ago charts the power of compound interest.

Industrial ecology revises rules of selection for the technologies, products, and enterprises that should survive. The industrial ecosystem may be optimized at several levels: around a product, within a firm, sector, or complete economy, and in a locality, region, or nation, or planet-wide.[5] Industrial ecology emphasizes that effective and efficient regulation happens only within a systems perspective.

Industrial ecology in some respects renames a process that has existed, implicitly, since the human economy began. Consider the origins of the paper industry in the manufacture of textiles 700 years ago.[6] The arrival of the spinning wheel in Europe in the 13th century sped yarn production, lowered the price of cloth, and increased its consumption. Linen was particularly affected. By the 14th century the supply soared of linen shirts, underwear, bedding, towels, and headwear. Increased use meant more and cheaper rags, and linen rags made the best paper. The burgeoning paper industry could expand production, lower prices, and seek new markets.

Formerly the skins of two to three hundred sheep or calves provided the pages for a single Bible. With the advent of cheap paper, the wages of the scribe became far the costliest part of a book. The wastes created by the spinning wheel created the conditions for success for Gutenberg's venture in mechanical writing. And saved a lot of skins.

We live inevitably in such a web of connections. We live off each other and sometimes off one another's wastes. We must now try more consciously to make use of waste products.

Some industries have moved in this direction. The history of the chemical industry is one of finding new uses for what were formerly waste products. An important waste product of the early nineteenth century was coal tar, generated in large amounts by gasworks making "town gas" for illumination. The systematic search for useful byproducts, initiated by German chemists, created the modern organic chemical industry.

Some dumps can be reconsidered as repositories of enriched ore to be mined. Many technologies exist to separate and purify. For example, electric fields can concentrate and facilitate the removal of "contaminants" from soils by electrosmotic purging.[7]

For five years, interest has been awakening in industrial ecology, imparting momentum to research in both universities and industry. Among the active academic institutions in the United States are the Rockefeller University, Harvard, Princeton, University of Texas at Austin, University of California at Los Angeles, and the National Academies of Sciences and Engineering. Industrial participants, pursuing improved practice as well as knowledge, include General Motors, AT&T, Motorola, Electric Power Research Institute, and Dupont.

The U.S. government has yet to focus on industrial ecology. Agencies able to contribute include the National Institute of Standards and Technology, National Science Foundation, Department of Defense, Department of Energy, and Environmental Protection Agency.

Congress hints at a new entity to stimulate and coordinate research and development, such as a National Environmental Technologies Institute. The environment and natural resources subgroup of the President's new National Science and Technology Council could develop strategy and options.

Improving America's industrial ecosystem will not necessarily create many new jobs. Already some new businesses specialize in "green design" and in brokering and reusing wastes. These will not absorb much labor, at least in the near term. Over the long term, new green industries should arise, as did paper and chemical dyes, but the long term is measured in generations.

Advances in industrial ecology should, however, lower costs through better materials management and reduced liabilities for hazards, and thus make firms fitter to survive. Good practice drawing on industrial ecology will often reinforce practices associated with continuous improvement and total quality management.[8] The on-demand generation of toxic chemicals needed for certain production processes exemplifies management that may honor both manufacturing and the environment.[9] Thus, the firms that excel environmentally are likely to excel generally.

What broad areas for research and practice should American engineers and scientists stress?

Consider the relationships between income and pollution (Figure 1). Rising incomes have provided countries, regions, and individuals with a sequence of environmental problems as well as the means for overcoming them. According to the World Bank, increasing per capita income early provides safe water and urban sanitation.[10] As income rises further, problems such as air quality worsen, but these also crest and lessen with prosperity.

In contrast, as the right-hand panels of Figure 1 show, the production of carbon dioxide and garbage have yet to abate with increase in per capita wealth. To counteract these trends, the critical directions for industrial ecology in countries such as the United States are decarbonization and dematerialization.

Decarbonization

Carbon matters because it is the main element used to spin the industrial web. Hydrocarbons — coal, oil, and gas — make up more than 70% of the material we extract from the earth. Along with the many benefits they provide as energy sources, hydrocarbon fuels also threaten greenhouse warming, smog, oil spills, and black lungs. The carbon is the environmental culprit. The hydrogen with which it bonds is essentially harmless from an environmental viewpoint.

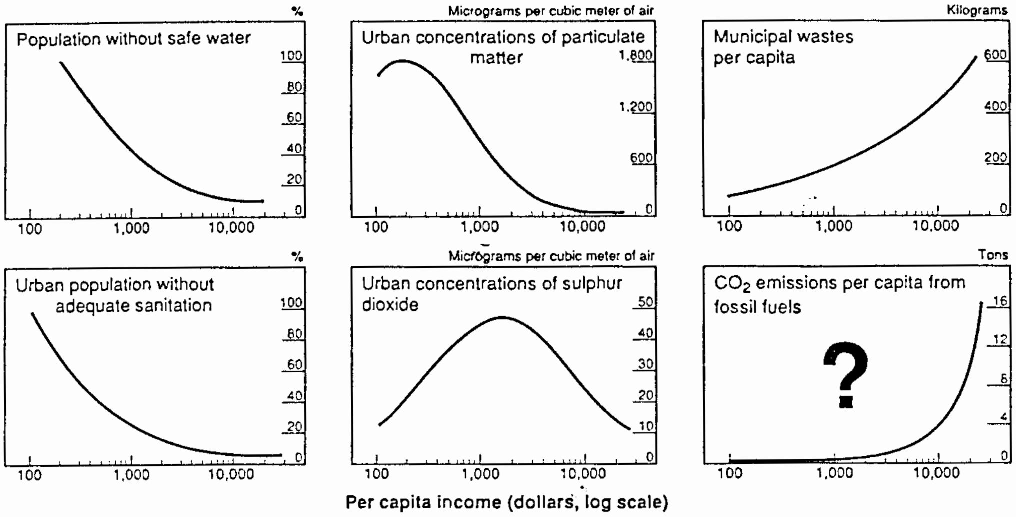

Figure 1. Relationship Between Environmental Problems and Income Growth, Based on Cross-Country Regression Analysis for Data from the 1980s (The question mark in the lower right panel indicates that an approach based on time series for individual countries may yield a different pattern for carbon dioxide emissions. Source: After World Bank, 1992.)

Decarbonization can be defined in several ways. A basic usage is the decline in tons of carbon used to generate a particular amount of energy, for example, a kilowattyear of electricity. To understand decarbonization, consider the composition of typical molecules of coal, oil, and natural gas (Figure 2). Coal, the most environmentally damaging fossil fuel, is loaded with carbon and raises measures of decarbonization. Natural gas (CH_2) is mostly hydrogen, and thus lowers the measures. Noncarbon sources, such as nuclear, solar, and hydro energy, lighten them further.

The growth of population and industry have raised U.S. and global carbon emissions. Dissecting this generality, however, exposes significant improvements. The relative performance over time of the industrial economy with regard to carbon is favorable: toward increasing efficiency of carbon use, toward decarbonization at a few percent per year. Globally, the carbon used to produce a unit of energy has fallen steadily to a half over the past 150 years (Figure 3), and the fall continues. The performance of the United States, which comprises a large fraction of world energy use, inevitably lies close to the global line.

Nations can achieve decarbonization with a range of strategies, as seen in Figure 4, which also shows energy efficiency gains.[11] For example, France's shift from coal to nuclear since 1950 appears dramatically.

The wealth produced per carbon burned also measures decarbonization. Figure 5 shows the improvement in the amount of carbon burned per

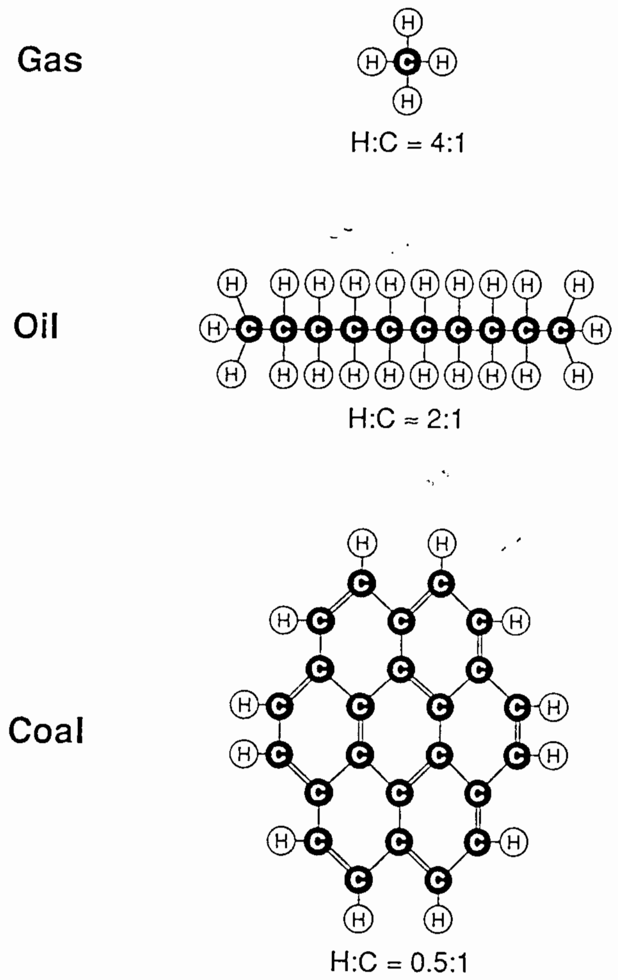

Figure 2. The Atomic Structure of Typical Molecules of Coal, Oil, and Gas, and Ratio of Hydrogen to Carbon Atoms

dollar of wealth in several nations with both the passage of time and rising income per person. Note that the rate at which the United States has advanced in decarbonizing its economy resembles that of Germany and Japan. Such measures provide a basis for international negotiations on the feasibility of targets and timetables for further progress, while taking into account the individual historic path of each nation. They also provide a quantitative way to recognize differences between advanced industrialized and developing countries.

A more elemental way to define decarbonization is as the evolution of the atomic ratio of hydrogen to carbon in the world fuel mix (see Figure 6).[12] Imagine all the carbon and hydrogen atoms used for energy during the past 150 years blended into one stew, and how this stew changes. If the trend toward decarbonization continues, the average primary energy source will

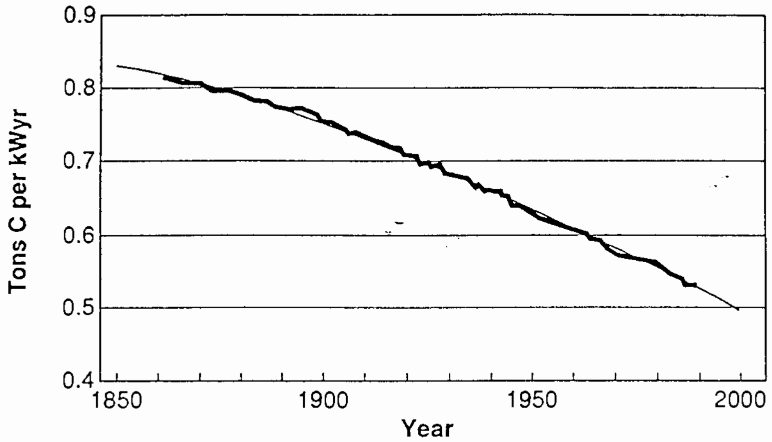

Figure 3. Decarbonization or the Changing Carbon Intensity of the Primary Energy for the World (Carbon intensity is calculated as the ratio of the sum of the carbon content of all fuels to the sum of the energy content of all primary energy sources. Carbon emissions in tons carbon per kilowatt year are: wood, 0.84; coal, 0.73; oil, 0.55; and gas, 0.44. Courtesy of A. Gruebler and N. Nakicenovic; see Ausubel, 1993.)

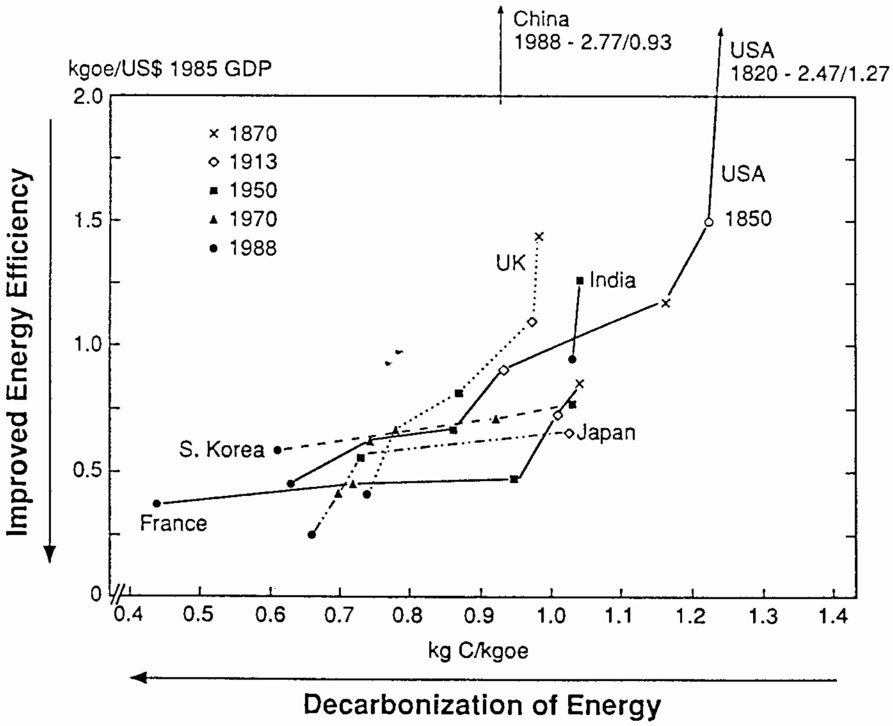

Figure 4. Trajectories of Energy Efficiency and Decarbonization for Selected Countries (Courtesy of A. Gruebler and N. Nakicenovic; see Ausubel, 1993.)

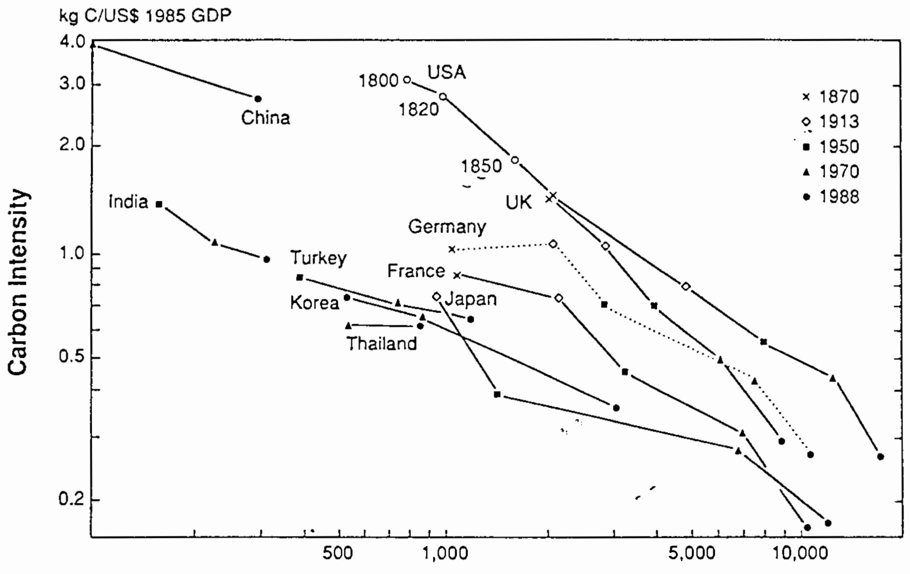

Figure 5. Diminishing Carbon Intensity of GDP for Selected Nations. Analysis Includes Fuelwood and Other Renewable Sources of Energy (Courtesy of A. Gruebler and N. Nakicenovic; see Ausubel, 1993.)

be CH around the year 2000 AD. Shortly after 2000 AD people will have to begin adding much hydrogen to maintain the ongoing decarbonization.

Decarbonization is the single most important fact to emerge from 20 years of energy studies. New technologies, as well as diffusion of existing technologies, are needed to advance America and the world further on the trajectory of decarbonization.[13] The trajectory represents the measurable, progressive realization of innovative opportunities. We can decarbonize by affecting either the numerator, the denominator, or both.

Switching from coal and oil to natural gas lowers the numerator. Many countries can leapfrog the oil era and go quickly to gas. Gas resources are enormous, yet tend to be overlooked. Virtually every nation, including China, that wishes to be self-reliant in energy has the opportunity through exploration and drilling for natural gas. If the wealthy nations of the North wish to lessen concern about conflicts between environment and development in the poor nations of the South, technologies for gas exploration and drilling and loans for gas infrastructure should top lists of priorities for development cooperation. Nations can also, of course, wean themselves from carbon fuels, and shift to nuclear and solar sources.

Extracting more energy from a given unit of fuel raises the denominator of decarbonization. Increasing the efficiency of turbines provides a timely means.

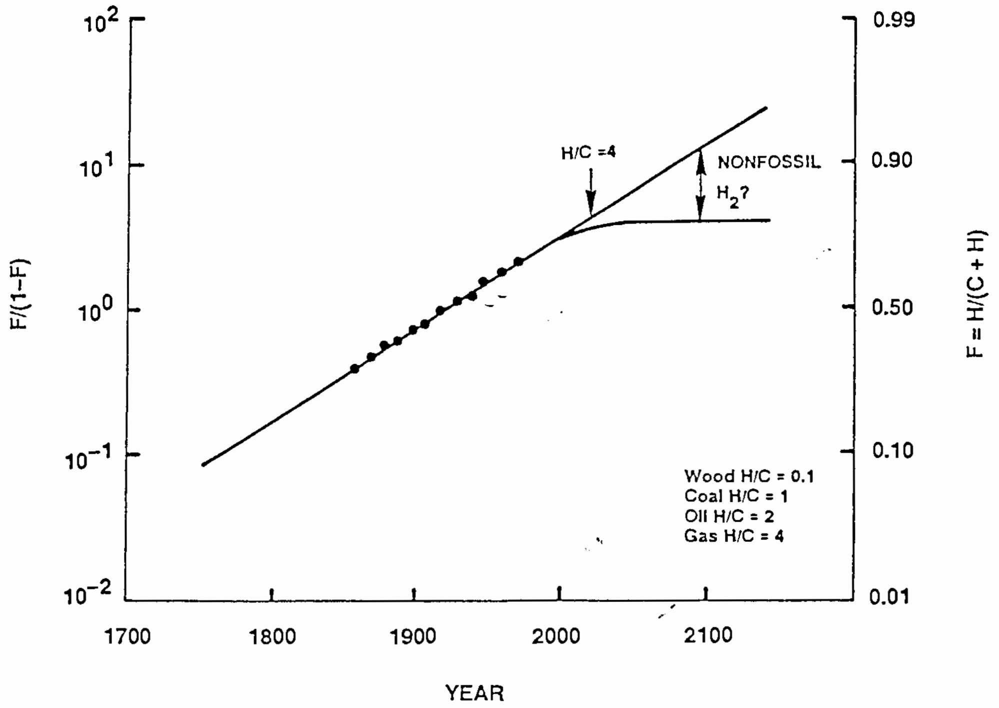

Figure 6. Evolution of the Ratio of Hydrogen (H) to Carbon (C) in the World Fuel Mix (The figure for wood refers to dry wood suitable for energy production; after Marchetti, 1985.)

Nonetheless, much more carbon will pass through our industrial metabolism before we squeeze the carbon from our diet. The globe may use about 500 billion tons more carbon over the next century, about twice the amount used since the start of the industrial revolution.[14] As industrial ecologists, we need to think of better ways to store and reuse all the carbon that will be burned. As implied earlier, natural gas will become the main source of carbon as coal and oil phase down.

A forward step in the industrial ecology of carbon is to steam reform natural gas into carbon dioxide and hydrogen. The basic recipe for reforming is to use nuclear or solar heat to cook CH_4+ $2H_2$ into CO_2 $+4H_2$ using appropriate catalysts to make the process more efficient. The hydrogen produced is used for fuel. The separated CO_2 must be disposed away from the atmosphere. It can be reinjected into the underground fields where the natural gas originated. Some of it can be profitably injected in oil fields to improve oil viscosity and enhance oil recovery.

In the long term, the globe must move to a hydrogen economy. Hydrogen is the immaterial material: its combustion produces only water vapor, a useful byproduct. Indeed, in the United States, French water costs more than Arabian oil.

Governments in the United States, Germany, and other nations have fostered hydrogen technologies on a small scale for a couple of decades. A much larger effort is needed. In the United States, hydrogen programs should move to center stage in the Department of Energy as well as the National Aeronautics and Space Administration and other agencies. The national laboratories, which search for post-Cold War missions, can play valuable roles in hydrogen R&D in collaboration with industry.

The transition to natural gas and hydrogen can be quite painless. Smoothing the transition is an important role for government. A *de facto* carbon lobby exists, led by the coal industry and miners and big oil. The energies of these groups can be channeled productively. Oil companies can benefit as much from natural gas as oil, and in fact several of the "majors" have already redefined their business toward what I have called "the light path," namely, natural gas and hydrogen.

Coal is harder. It will be tough for firms and shareholders to accept that the collieries will be valued at zero or less within a few decades. The key point for labor is that the job is tunneling, not mining coal. An enormous need exists for digging and tunneling, for high-speed underground transport of people and goods, including water.

At the international level, decarbonization meshes attractively with U.S. foreign and trade policy. As one illustration, decarbonization could help defuse the Persian Gulf. Enhanced reliance on natural gas would reduce the amount of oil imported, cut revenues to Iran and Iraq, and shrink the Persian Gulf arsenals.

Dematerialization

The declining weight of beverage cans and computers suggests dematerialization. Like decarbonization, dematerialization can be formally defined in several ways.[15,16] The decline over time in weight of materials used in industrial end products, or in the "embedded energy" of the products, provides a starting point. We can also measure dematerialization at the stage of resource extraction, at the level of the consumer, and in terms of waste generated. Dematerialization can be assessed in absolute terms, per unit of economic activity (GDP), and per capita.[17] Volume as well as weight matters.

Dematerialization could help the environment greatly. Less material could translate into lower demands on the landscape and smaller quantities of waste generated in both production and consumption. The simple amount of stuff creates numerous environmental problems. Although many pervasive products have become smaller and/or lighter, the question remains of a widespread, long-term trend toward dematerialization.

Evidence cited for dematerialization includes not only more compact products. Per capita consumption of selected materials, such as steel, has declined in advanced industrialized countries. Total industrial solid waste generation has declined in the United States since about 1980.

However, the overall picture about dematerialization is not so sanguine. Generation of municipal solid waste increased 1.6% per year per capita in the United States between 1960 and 1990. Potential factors offsetting efficiency gains are numerous. Economic and population growth come first. But also, if smaller, lighter products are inferior in quality, more units will be produced and discarded. High repair cost, fads and fashions, and product innovation can all materialize.

A look at the relative consumption of seven materials in the United States economy from 1900 to 1990 (Figure 7) suggests the varied destinies of materials. A good or service that required five kilos of lumber in 1900 needs a half kilo today. The intensity of use of steel and lead has dropped to half. Aluminum, a light-weight, high-strength structural material, and phosphate, a key ingredient in fertilizer, grew rapidly from about 1940 into the 1970s, then began to fall. Plastics, light and bulky and often environmentally troublesome, have soared and only recently show signs of leveling. Once again, sustainable rates of change are a few percent per year.

Paper provides an interesting case study (Figure 8). Total annual paper consumption in the United States climbed steadily from a couple of million tons in 1900 to more than 80 million tons in 1990. Paper consumption per capita rose less rapidly, fluctuated for a period in the

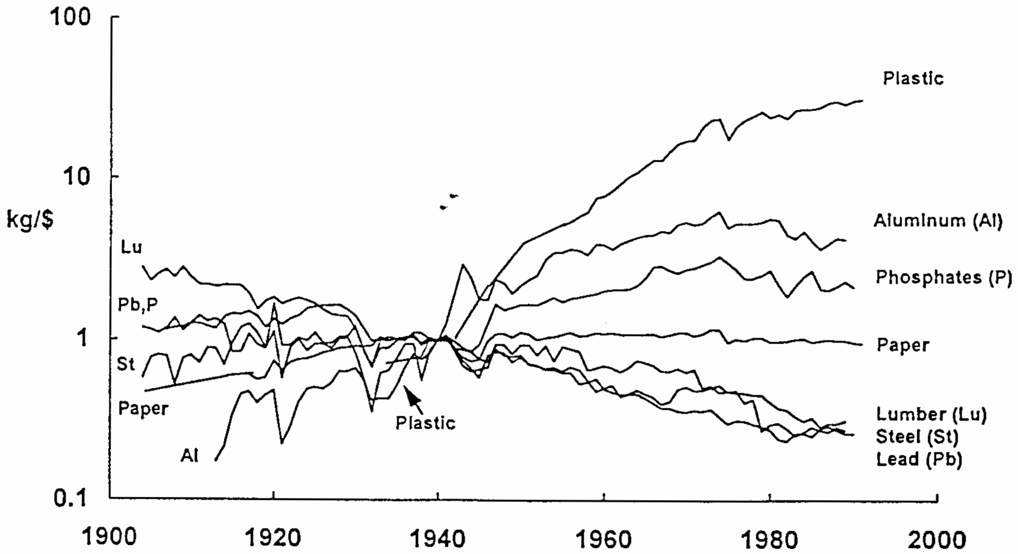

Figure 7. Intensity of Use of Selected Materials in the United States, 1900–1990 (Production data are divided by GNP in constant 1982 dollars and normalized to 1940. Sources of data: U.S. Bureau of the Census, Statistical Abstracts of the United States, various years.)

1970s, and then rose again as the information revolution spread. Americans now each use about two pounds of paper per day. The paper news is better when we look at consumption per unit of GNP. Paper appeared to fully penetrate the U.S. economy by about 1930, and held its role to about 1975, when some dematerialization began. As an aside, note that during World War II, America drastically reduced relative paper use. When a society acts, the need for paper is less.

The way we live is at the heart of materialization. Spatial dispersion of population materializes. Migration from urban to suburban areas requires more roads and single-unit dwellings. The shift from larger to small families materializes (Figure 9). The number of residents of an American household has declined steadily from about five in 1900 to fewer than three at present. This trend implies more consumption of virtually every material.

Dematerialization directs industry and all of society to be more concerned about the eventual fate of its manufactures. It confronts us with the question of whether society can continue in its "throwaway" mode. It suggests new environmental design criteria and a new generation of sophisticated materials research. Of course, the quest for dematerialization can interact in complex ways with efforts to recover and reuse wastes. Substituting plastics for steel in a car may reduce weight and increase fuel efficiency, but decrease possibilities for recycling.

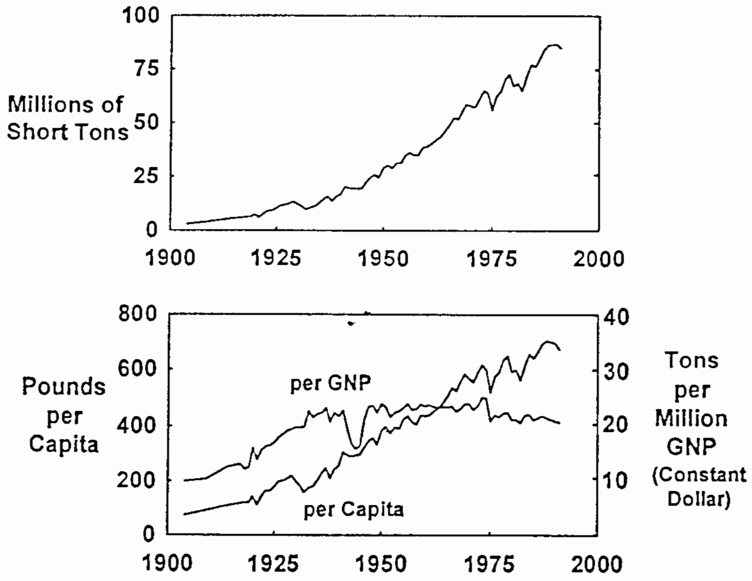

Figure 8. Upper Panel: Total Paper Consumption in the United States, 1900–1990. Lower Panel: Paper Consumption per Capita and per Unit of Economic Activity (GNP) in Constant 1982 Dollars in the United States, 1900–1990 (Sources of data: U.S. Bureau of the Census, Statistical Abstracts of the United States, various years.)

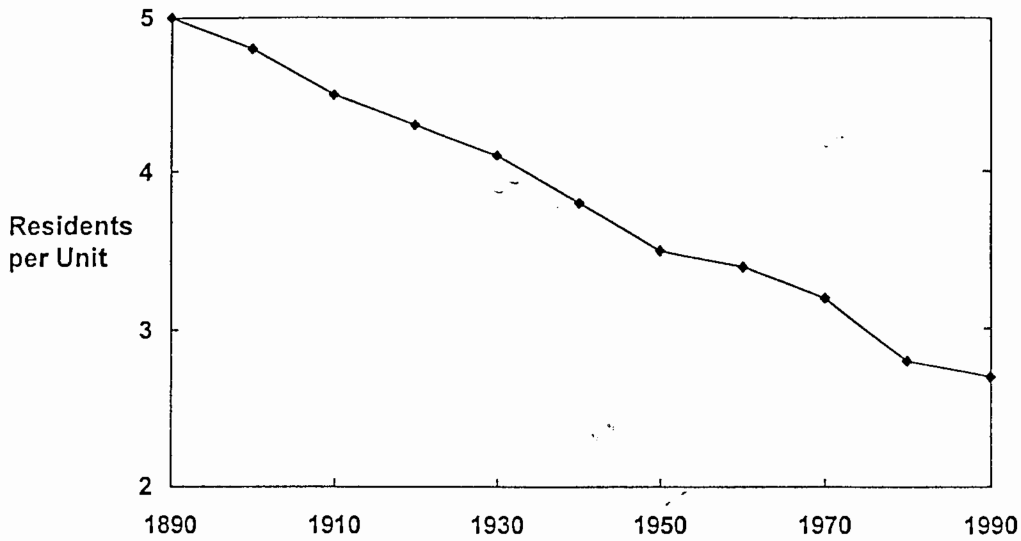

Figure 9. Number of Residents in a U.S. Household, 1900–1990. (Sources of data: U.S. Bureau of the Census, Statistical Abstracts of the United States, various years.)

Sound long-term studies of historical and potential dematerialization can help set national goals. The U.S. Environmental Protection Agency has struggled with direction for its Office of Pollution Prevention in the absence of reliable knowledge about long-term trends. Such studies will also help sort the numerous economic and regulatory instruments that can affect material flows. These include mandating take-back of products, taxes on production of virgin materials, fees for waste disposal, and facilitating waste exchange.[18]

Decoupling materials and affluence will be difficult, harder than decoupling carbon and prosperity: Objects confer status. The scepter and the orb identify the King.

Environmental Audits

What are ways to stimulate innovation and diffusion for environmental technologies? The spread of technology is after all a matter of social acceptance, so it is logical to look to social processes to green the industrial ecosystem. Encouraging, or possibly mandating, the performance, and public reporting of annual corporate environmental audits could help.

Auditing for financial health, performance, and veracity is generations old. An entire profession has developed to provide independent assessments of "the books" of corporations. Precipitated in the United States by the stock market speculation of the Roaring Twenties and the

Crash of 1929, certified audits have proven a pillar for sound investment and sustained economic growth. The Securities and Exchange Commission (SEC) is the U.S. federal agency with the main responsibility for mandating corporate reporting.

Shareholders of companies certainly have legitimate concerns about the environmental performance of a firm, not only because of general corporate responsibility, but because of potential liabilities. Numerous companies have begun to assess internally their environmental performance on a more systematic basis, and to provide environmental reports voluntarily to outside parties. A coalition of companies formed the Global Environmental Management Initiative in 1991, in part to define environmental information companies should share with investors.[19]

Investors, investment professionals, and environmental organizations formed the Coalition for Environmentally Responsible Economies (CERES) to address environmental questions from the perspective of the marketplace. They listed environmental reporting as one of the "Valdez Principles" for environmental conduct developed subsequent to the oil spill in Prince William Sound, Alaska.[20] Regular and reliable reporting could be stimulated and coordinated internationally by the Business Council for Sustainable Development and the World Engineering Partnership for Sustainable Development. The Council of the European Economic Community approved regulations and guidelines in this area in 1992.[21] The U.S. government should clarify its position.

Most large corporations have a vice president or other senior executive responsible for environmental affairs. The boards of directors of most companies receive periodic internal reports on the environmental performance, challenges, and liabilities of the company. In the United States, the Clean Air Act and other laws and regulations already require the collection of much information. Thus, personnel to provide key information and the information itself exist for many corporations, and improved reporting should cost little.

Although key indicators of environmental performance for companies would vary by sector, much could be common. Common or widely reported information might describe energy and materials use efficiency and waste reduction, as well as fines, lawsuits, and costs of compliance. Success would depend on identifying a small number of indicators that are true and measurable benchmarks. Safety performance and financial audits might provide analogies. These also show the pitfalls of audits, which can tend to trivia, manipulation, and obscurity, and also raise subtle issues of confidentiality and liability. A quite useless industry of cranking out and reviewing environmental impact statements already burdens firms and government.

Presumably, companies would want to impress investors with the ways they improve with respect to the environment each year. The report could thus help give green impetus and goals to the internal corporate environmental staff and to the corporation as a whole. "Sunshine" is often healthful. A new independent profession of Certified Environmental Auditors might confirm the corporate reports.

The sum of the corporate reports should in turn begin to produce the data for national and global pictures. These data would provide not only indicators of overall advances in environmental performance, but also authenticated sources for arguments in cases where national expenditures for compliance may exceed plausible benefits. They may also economically provide valuable data about national compliance with international agreements.

The firms of the private sector can lead, but the public sector and consumers also act large roles in the industrial ecosystem. It would be valuable for government at all levels to report on its efforts for waste reduction, in the fresh green sense of the term. Nonprofit organizations, such as universities, ought also to assess and report regularly on their environmental performance.

Finally, we need to caution that optimizing at the level of the enterprise may not optimize for the whole system. Where rags can become paper, we should not mindlessly trim our cloth.

Conclusion

Over the long haul, Green Evolution will occur because we progress a few percent per year along the trajectories of decarbonization and dematerialization. These can key a superior industrial ecology. Technologies supporting natural gas, hydrogen, and efficiency of energy and material use emerge powerfully. These should bring corollary benefits in international relations and trade, at least for the United States. The outlook for job creation is uncertain, but investing in gray rather than green industries is surely short-sighted. Political systems can support research, spur the diffusion of knowledge, and help build feedback into industrial systems. The concepts outlined here provide the reliable long-term orientation that make the operators of the system good and confident navigators.

Acknowledgments

I am grateful to Robert Frosch, Arnulf Gruebler, Perrin Meyer, Nebojsa Nakicenovic, and Iddo Wernick for suggestions and assistance.

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