INDUSTRIAL ECOLOGY: DEPRECIATION, WASTE AND POLLUTION

by

R. U. AYRES*

98/64/EPS

This working paper was published in the context of INSEAD's Centre for the Management of Environmental Resources, an R&D partnership sponsored by Ciba-Geigy, Danfoss, Otto Group and Royal Dutch/Shell and Sandoz AG.

* Sandoz Professor of Management and the Environment at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France.

INDUSTRIAL ECOLOGY: DEPRECIATION, WASTE AND POLLUTION

Robert U. Ayres

Center for the Management of Environmental Resources
INSEAD
Fontainebleau, France

July 1998

Abstract

Industrial ecology, as it is called, is the study of materials and energy flows and transformations, both in an economic system and across its boundaries. Cross-boundary impacts on the biosphere have economic implications because they affect (usually adversely) important environmental services to humans. The services in question range from climatic stabilization and nutrient (C, N, S) cycling to food supply and waste assimilation. Also, the environment is our source of raw materials for production, both renewable and non-renewable. Thus industrial ecology overlaps both resource and environmental economics.

The paper discusses a number of economic implications of cross-boundary flows of energy and materials. One of them is that exponential economic growth, along the current materials (and energy)-intensive trajectory, is also utilizing exponentially increasing amounts of raw materials. All materials extracted from the environment, of which fossil fuels are only the most obvious example, eventually become wastes and emissions. While not all emissions are equally harmful, growth is creating increasingly unsustainable pressures on the environment and threatening the continued availability of essential environmental services. This means that either growth must cease, or its character must change.

Ruling out the former option implies a need for radical `dematerialization' of the economy [e.g. von Weizsäcker *et al* 1994]. In particular, it implies that dissipative uses of materials must be phased out, while durable goods must be made to last longer and provide more services during their life cycles. The economic implications of this imperative are discussed.

Background

The fact that materials extracted from the environment must ultimately either be embodied in durable assets or return to the environment as wastes or pollutants is no longer a new insight. Nor is the implication that historical pattern of materials intensive economic growth cannot continue indefinitely without serious and irreversible damage to the environment, quite apart from the likelihood that such "essential" resources as petroleum will not continue to be available at ever-declining prices.

Neither is it a new idea that the availability of cheap fossil fuels (and other natural resources) have been a key driver of past economic growth: falling energy (and other raw material) prices triggered increasing demand, including many applications of mechanical power to replace human labor. This, in turn, kept real prices of natural resources and mechanical power on a continuing long-term downward trajectory, notwithstanding the exhaustion of original resource endowments in areas that were the first to be industrialized.[1]

Another important growth `engine' of the past has been the positive feedback loop involving scale economies and the so-called `experience curve' which also keeps real costs falling and thus increasing the demand for manufactured goods. In fact, one of the dilemmas facing present-day governments — although largely unrecognized — has been that most of the historical growth in labor productivity has been in the manufacturing sector. Manufacturing has been the major beneficiary of both falling energy prices and increasing scale and the associated returns to scale. The shift from manufacturing to services — now approaching 80 percent of the US economy — has sharply diluted the impact of both of these historical `growth engines'. Meanwhile, as will be noted later, the expected productivity gains from information technology have yet to be demonstrated.

Still another well-known fact is that environmental problems and unpaid social costs associated with all materials/energy intensive activities have already created pressures to make materials and energy producers pay more (and more) to reduce waste and pollution. This will make energy and materials significantly more costly to users. High cost energy will encourage users to be more efficient and to seek alternatives where possible. Many of these gains in materials/energy productivity must be achieved — in effect — by substituting labor or capital for energy or materials. (Insulating houses to reduce the need for hydrocarbon fuels would be an example; it is perfectly possible to cut the energy requirements of most buildings by 90 percent, through careful design to utilize waste heat and solar energy). Other gains can and will be achieved by extending the useful life of material products by increasing the level of re-use, repair, renovation, remanufacturing and recycling.

Nevertheless, the implications of this set of non-new ideas, taken together, has some important economic implications that have not yet been thought through. Thanks to (lack of) economies of scale, recovery, repair, renovation and recycling are inherently more labor-intensive than original mass production. (This fact accounts for the current tendency to discard and replace rather than repair.) Thus increased re-use, renovation and remanufacturing appear to be very desirable from the standpoint of reducing unemployment. But the other side of the coin is that they also *ceteris paribus* reduce labor productivity. Increasing resource productivity has a downside in the form of reduced economies of scale for the raw materials processing industries and the mass producers.

On the other hand, continued economic growth itself continues to be an important political and social objective. Indeed, the needs of aging populations and increasing health-related entitlements, not to mention more investment in education and research, demand that economic growth should accelerate, if anything. A stark question arises: how is future economic growth to be reconciled with a static or declining rate of increase of labor productivity? Is it possible? The rest of this paper considers this question, among others, from several points of view.

Economic growth and wealth

Economic growth is conventionally measured as increasing national income, or national output (i.e. GNP) in monetary terms. GNP, in turn, is the sum of all value added by labor or capital by national entities which is also equal (by definition) to the sum of all revenues received by the same entities as wages, dividends, interest, or fees. GNP is thus interpreted as returns to labor and capital. Net national product (NNP) is GNP less depreciation, or capital allowance. Capital, in this case, is defined as the accumulation of investment less depreciation. However, GNP can be interpreted as returns to capital alone, if capital is defined to include `human capital' as well as so-called natural capital.

It is standard practice to measure economic growth as increasing GNP (which is really a measure of economic activity) rather than increasing wealth *per se*. In the case of individuals, households or firms wealth consists of financial and tangible assets. The latter category includes real property, buildings, equipment and cultural objects and `collectibles' such as works of art. These assets, valued at market prices or (in the case of equipment) initial cost less depreciation, constitute `book value'. There is another accounting category for `good will' in business, to account for the market value of a viable enterprise over and above its book value. Brand names, franchises and the like fall into this category. Finally, to calculate net equity, debts and receivables must be subtracted from, or added to, the total of other assets.[2] In practice, equity in proprietorships, partnerships and firms with non-traded securities cannot be valued directly. Valuations are imputed by the Federal Reserve Bank by means of a so-called `flow-of-funds' model that equates assets and liabilities

It is tempting to extend this scheme to the national level. Indeed, calculations of national wealth were a standard feature of the annual *Economic Report of the President* to the Congress of the United States until the early 1990s. Tangible wealth for households (including non-profit institutions) was subdivided into real property (land and structures), and consumer durables, mainly automobiles. Tangible wealth for government consisted of infrastructure, buildings, vehicles and military equipment. However, in the case of business, no separate estimate of tangible wealth was made. Instead, it was included in business equity, subdivided between incorporated and non-incorporated businesses. Since business equity is ultimately a financial asset of households (albeit ownership is largely indirect, through a maze of other financial institutions) it seemed unnecessary to subdivide business equity into tangible and financial components.

National wealth, thus calculated, showed a satisfying annual growth (see *Table 1*). However, the standard scheme omitted two important items. One was expected future earnings from labor, which can be equated to the present value of the stock of knowledge and skill that enables workers to perform economically valuable services. This knowledge and skill should be counted as national wealth. In reality, it is the basis of which many hard-headed lenders are eager to provide credit to individuals, and on which governments are able to calculate future tax revenues and guarantee future payments of interest on debt, or social security and Medicare payments to individuals.

The discounted present value of expected future earnings by workers bears the same relation to financial wealth as payments to labor (i.e. wages) bear to payments to capital (i.e. dividends and interest) in the national accounts. Putting it another way, if financial wealth can be regarded as the present value of future returns to tangible and/or financial capital, then there should be a corresponding term representing the present value of future returns to labor, or `human capital'.

The second omission of the standard scheme for calculating national wealth is the various forms of `natural capital' — from topsoil and biodiversity to climate — that provide essential services to the economy. The monetary value of these services is obviously very difficult to estimate. (To do a better job at this is surely one of the chief challenges of environmental economics for the next decade). Unquestionably, failure to include natural capital in the system of national accounts (SNA) has led many politicians (and economists) into a thoroughly misleading habit of treating income from the sale of natural resources as `rents' — part of national income — while failing to make any compensating allowance for the reduction in asset stocks.[3] To correct for this failure is a part of the UN's motivation for developing a `green' SNA, although the effort seems to have stalled.

An issue closely related to the problem of quantification of natural capital is the argument between `strong' vs. `weak' sustainability. Very briefly, advocates of the `weak' version believe that produced capital (and goods) can be a reasonable substitute for natural capital and services derived therefrom. To the extent that the services in question are recreational or aesthetic amenities, there is a valid argument for weak sustainability. (A holographic picture or movie of a mountain may be enough for many people). Similarly, to the extent that the natural capital in question is a raw material, technological substitutes are generally plausible. But to the extent that the environmental services in question are necessary for the long-run survival of human life on the planet — and climatic stability, stratospheric ozone, biodiversity and the nutrient cycles are among those services — the case for weak sustainability seems very weak indeed. Technology offers no plausible substitutes. However, while further comment on these topics is certainly relevant to industrial ecology, it is beyond the scope of this paper.

What is relevant here is the fact that tangible capital assets belonging to households are also a significant component of national wealth. Moreover, a major part of financial assets — another component of national wealth — consists of expected future returns to tangible capital assets belonging to businesses. If national wealth is to increase it is natural and logical to assume that tangible assets must correspondingly increase in value, if not in quantity. A question similar to the one raised at the end of the last section now arises: how can the *value* of tangible assets increase if the *quantity* of raw materials and energy consumed by the economy is to decrease (as environmental constraints require)?

Another important point that is worth emphasis is the following: liquid assets are financial, not tangible. But financial wealth can rise and fall for a number of reasons, some of which are not very well understood. The decline of Japanese financial wealth since 1989 and that of the rest of east Asia since 1997, while US financial wealth was doubling (or more) illustrates this point well enough. Be that as it may, the bulk of financial wealth still rests on a tangible, material basis. Information may be increasingly important, but only a very small fraction of total wealth (as yet) can be attributed to `pure' information, such as stored data, chemical formulae, blueprints, or computer software.

Dissipation and dematerialization

A further point of some importance is the following: Whereas structural materials *embodied* in long-lived tangible assets obviously contribute directly to tangible wealth, there is no such direct link between *dissipative intermediate* material flows and wealth creation. Such flows are equivalent to assets that depreciate totally during a single use. In fact, dissipative intermediate materials add nothing to wealth *per se* but contribute a great deal to pollution and environmental harm. At first sight this statement may seem hard to justify. Surely lubricants *reduce* wear. Detergents and solvents *remove* dirt (or undesirable contaminants), which add to, or preserve, value. This is true, but it reflects the fact that the service function does not inherently require dissipation. In principle, most lubricants, solvents (and even detergents) could be recovered and reused. In other words, some materials that are normally dissipated could be regarded as capital assets that happen to be very wastefully used. On the other hand, this is not true for fuels, or for many process chemicals such as sulfuric acid, caustic soda, lime or chlorine.

Returning to the restricted domain of tangible man-made capital, it is worth recapitulating a point made previously. The difference between a capital asset and an intermediate good in the economy is essentially that a capital asset is re-usable, whereas an intermediate good is immediately converted into something else, either another good or a waste. Georgescu-Roegen introduced a useful distinction between `*funds*' and `*flows*' [Georgescu-Roegen 1979]. Capital is a fund, whereas intermediates are flows.

On reflection, it is clear that some, but not all, intermediates are converted into other goods. There is a large class of intermediates that is dissipated rather than transformed. Fuels, lubricants and solvents are only the most obvious examples. For tax purposes the difference between an intermediate good and a capital item is essentially a matter of re-usability and useful lifetime. Material goods that are consumed or dissipated do not contribute directly to tangible real wealth, although they may be a necessary part of the current production process.

Evidently the monetary value of tangible produced wealth, as discussed in the last section, is strongly dependent on the assumed rate of depreciation of durable goods (as determined by the tax authorities). Obviously the real value of tangible produced wealth, which may be higher than the value for tax purposes, is nevertheless dependent on the real rate of depreciation. What follows is that cutting the rate of depreciation of durables would increase the rate of accumulation of tangible wealth as well as financial wealth derived therefrom. On the other hand, reducing or eliminating the use of consumables or intermediates has no direct impact on the accumulation of wealth.

Suppose, for purposes of argument, that all intermediate flows of materials that are not embodied in final products (i.e. materials that are `used up' and dissipated within the production process) could be either recovered and reused over and over, or magically eliminated by process changes, *without affecting the quantity or quality of durable goods and tangible assets*. Suppose, too, that durable goods became even more productive (of services to users), and even more durable. Suppose, finally, that after one `life' they could be renovated or remanufactured indefinitely (as old houses in Mediterranean countries are). All of these changes would sharply increase the output of the economy per unit of material input. They would constitute a major *dematerialization* of the economy.

From the environmental perspective, dematerialization — by conserving value-added and by reducing dissipative uses of materials — has enormous benefits in terms of reducing the need to extract and process primary materials. It is, after all, the mining, concentrating and refining processes that generate the vast bulk of industrial wastes and pollutants. Recovery and re-use of a ton of copper wire or lead batteries not only saves a significant value-added. It also saves hundreds of tons of mine waste, explosives and fuel used in mining, chemicals used in concentration, arsenic and other toxic heavy metals that would otherwise be mobilized and dispersed via dust or slag, and so forth. (See *Figure 1*).

As a matter of interest, I have compiled a set of `multipliers' showing, on average, how much of each of a number of inputs and outputs are eliminated for each ton of metal that is recycled instead of being mined, concentrated, smelted and so on. This data, which allows for the materials consumed in the recycling process, is shown in *Table 2*. For instance, on the input side, a ton of recycled iron eliminates the need for extracting and processing 17.3 tons of ores (including overburden), limestone, coal, etc. For copper the corresponding number is 612 tons. For uranium, silver, gold and platinum the numbers are nearly astronomical. On the output side there are comparable savings, mainly of wastes and pollutants. Obviously inputs and outputs must balance.

Admittedly, a comprehensive dematerialization scenario would involve extensive industrial restructuring (eco-restructuring). It is impossible to calculate *a priori* the impact of such a restructuring on aggregated financial wealth. The financial value of stocks in oil companies, for instance, would decline. But other stocks (in remanufacturing enterprises, for instance) would increase in value. What can be said, however, is that the utility of real final services consumed by households would be unaffected (by definition), while the real disservices resulting from environmental pollution would be abated considerably.

Is the economy already dematerializing spontaneously?

There is a widespread impression, even among sophisticated economists, that the economy of industrialized countries is already well advanced in the process of dematerialization, thanks to micro-miniaturization and "high tech". For instance, consider the following two quotes:

> "Fiber-optics has replaced huge tonnages of copper wire, and advances in architectural and engineering design have made possible the construction of buildings with much greater floor space but significantly less physical material than the buildings erected just after World War II. Accordingly, while the weight of current economic output is probably only modestly higher than it was a half century ago, value added, adjusted for price change, has risen well over threefold." (Alan Greenspan, from speech at The Conference Board, NY, 10/16/96:

and

> "America's output, measured in tons, remains about as heavy as it was a century ago, even though real GDP, measured in value, is twenty times greater. The main reason for this striking shift from material goods to intangibles, described in a speech in 1996 by Alan Greenspan, chairman of the Federal Reserve Board, can be identified as the rising proportion of total cost of the "knowledge" content of goods and services, relative to materials and energy" (Frances Cairncross, *The Death of Distance: How the Communications Revolution Will Change Our lives*, Chapter 8, 1997)

According to Greenspan, the weight of current (US) output is only slightly higher than it was half a century ago (say 1950), but that it is worth three times as much (in real terms). Cairncross says that output a century ago (say 1900) weighed about as much as today, but that today's value is twenty times greater.

Of course, it makes no real sense to weigh the GNP, which is a monetary aggregate. It is possible to weigh the raw material inputs to an economy, given a set of assumptions and conventions.[4] To do so, however, it is first necessary to define a "raw material". (If air and water are included, the mass will be far larger than all other inputs combined.) If air and water are excluded, but crude metal *ores* (e.g. gold and copper) are included, one gets another set of big numbers. Based on this convention, gold and copper ores plus fossil fuels account for most of the mass of inputs. But then one needs another convention to deal with crude ores associated with imported metals and gems (e.g. diamonds) but left behind in or near the mines. For instance, a few hundred tons of platinum used each year in the US for automotive catalytic convertors requires hundreds of millions of tons of crude ore to be dug up and processed in South Africa. And that is before trying to estimate agriculture! Does one include the grass consumed by cattle among the mass inputs?

Of course, outputs may weigh a lot less than inputs. But, again, a lot depends on what one chooses to count as an output. Does one count corn and hay fed to animals on the farm? Are logs taken from the forest an output (of forestry) or an input to lumber and paper? In general, lots of outputs are inputs for other "downstream" products. Even so-called "final goods" are, in a sense, producers of immaterial final services. By this test, *all final outputs are immaterial, like electric power and information, and therefore weightless*. In view of all this, it would seem that Greenspan and Cairncross were probably talking about finished products, not final services.

But the ambiguities are not entirely resolved. In the case of metals, it might be semi-reasonable to count the weight of "finished materials" since there is relatively little difference between the weight of steel produced in the US and the weight of steel products (89 MMT in 1993). About 51 MMT of the steel produced was actually recycled scrap. Domestic pig iron inputs were only 48 MMT. (The weight difference consists of slag, CO_2 and some other minor inputs and wastes). However the mass of steel, while the most important (finished) metal in tonnage terms, was almost insignificant compared to the weight of sand, gravel and crushed stone. These last three categories amounted to nearly 2 billion metric tons in the US in 1993 (compared to 1.5 billion metric tons in 1975). Inert minerals constitute the major part of the weight of buildings, roads and other infrastructure. Portland cement (made from limestone, shale and other types of stone) is the single most important component of construction materials in terms of energy inputs and dollar value, but not in terms of weight — only 66 MMT or so.

To put it into perspective, 1993 US production of all non-ferrous finished metals together was only 6 MMT (of which about 2 MMT was actually recycled scrap). The weight of refined copper produced in the US in 1993 was about 2.36 MMT of which just 1.82 MMT was destined for copper wire. (The 1947 figure was 0.78 MMT).Thus, while Alan Greenspan may be right that fiber optics have replaced "huge tonnages" of copper wire, the adjective "huge" must be understood in a relative sense. Glass fiber may have replaced a significant part of the demand for copper wire, but probably not (yet) as much as half. Copper wire, in turn, accounted for less than one tenth of one percent of all `finished materials' generated by the US economy, even if we disregard fuels.

Consider fuels. In this case the main difference between inputs and outputs of "finished" fuels like gasoline, diesel oil and gas, would be mass lost in processing plants and refineries. For dry natural gas and crude oil the losses from well to burner are of the order of 10%. In the case of petroleum products, "finished" outputs also include petrochemical feedstocks, coke and asphalt. But the fuels are subsequently burned, either to generate heat (for space heating, hot water, cooking, etc.) or to produce mechanical power for road vehicles, aircraft, tractors, off-road machinery, etc. Needless to say, heat and mechanical power are weightless. In the case of coal, some is exported, some is made into coke for the steel industry (plus coke oven gas), but most is consumed by electric power plants, generating electric power (with no mass at all, but high value) and producing a lot of solid waste — from ash and flue gas desulfurization sludge — plus combustion products.

Consider the fate of raw fuel inputs, which was about 2 billion metric tons for the US in 1993. In fact, it mostly combined with atmospheric oxygen. The combustion of hydrocarbon fuels in the US, in 1993, generated around 5.2 billion metric tons of CO_2, the most important "greenhouse" gas. This may be a slight underestimate, since some of the hydrocarbons produced by refineries do not oxidize immediately (asphalt and plastics, for instance) but they almost all oxidize eventually. In addition, the combustion of fossil fuels generated something like 80 million metric tons of ash — about the same as the tonnage of steel produced in that year — plus 19.5 MMT of SO_2 and 21 MMT of NO_x. Clearly Greenspan and Cairncross are not counting these wastes as part of the mass of economic outputs. In physical terms, however, they surely are outputs. In fact, the wastes and pollutants from fossil fuel combustion alone far outweigh all the "goods" produce by the economy.

Consider forest products. Inputs (raw wood harvested) amounted to 520 MMT in 1993., not counting timber residues left in the forests (about 145 MMT). About 200 MMT of this weight was moisture. Finished wood products (lumber, plywood, particle board) weighed about 61 MMT. Finished paper products amounted to 83 MMT, which included some paper made from imported wood pulp from Canada and some recycled waste paper. The output weight also included 3.7 MMT of fillers and other chemicals embodied in the paper. Again, the difference between inputs and output weights was very large. Quite a lot was lignin wastes from the paper mills which are burned on site for energy recovery, but some of which still ends up as pollution. A lot of harvested wood (about 168 MMT, including paper mill wastes) was burned as fuel, producing about 230 MMT of CO_2 as a by-product. Should this be counted as part of the weight of outputs?

Against these numbers, the weight of most consumer products is trivial, of course. The 15 million motor vehicles produced each year in the US weigh around 200 MMT or so (including trucks) — about the same as US annual food consumption! All other consumer products, except structures, must add up to less. For instance, the weight of all textiles, including cotton, wool and all synthetics, amounts to only around 5 MMT. Products of textiles must be of the same order of magnitude. The weight of all electrical goods produced in the US has not been determined, but it cannot exceed 20 MMT (of which copper wire accounted for 1.8 MMT in 1993, or less than 10 percent).[5] Most of the weight of electrical goods is miscellaneous" materials). The mass of all plastics produced each year is also around 25 MMT. (The total mass of all organic industrial chemicals in 1993 was a bit over 40 MMT).

It is commonplace to point out that electronic circuit elements (silicon chips) have been shrinking dramatically in size since the first electronic computers were built in the 1940s. This is true. However, it does not follow that the total mass of materials consumed in the manufacture of computers has declined. On the contrary, it is easy to show that the mass of materials consumed in the industry has also increased. The weight of an early computer c. 1955, as now, consisted mostly of peripherals. The first commercial computers, the UNIVAC I and the IBM 701 (c.1953) occupied — with peripherals, such as DC power supply, tape drives, card readers and printers — a floor space of at least 40 square meters, not counting space required for special air-conditioning units. The machines themselves occupied a volume of at least 6 cubic meters and contained several thousand vacuum tubes (for logic circuitry) and cathode ray tubes (for memory). By 1955 there were probably 20 comparable machines in the US. Including peripheral equipment they probably weighed as much as a car, or around one metric ton apiece (mostly steel racks). Call it 20 metric tons each, or 400 metric tons altogether.

Now jump to the present. Domestic shipments of personal computers (PCs) in 1997 were about 30 million units [The Economist June 13 1998, p.24]. These were lap-top and desk-top units. The average weight of each desktop unit is over 10 kg. (of which the monitor accounts for something like half, while laptops average something like 3-4 kg. So, at 6-7 kg per unit, the overall mass of small computers shipped in the US in 1997 — disregarding workstations, `mainframes' and supercomputers — must have been around 200 million kg or 200,000 metric tons. (The mass of silicon chips contained therein was much smaller, probably less than 1000 metric tons). Other types of computers, while fewer in number, were also bigger and heavier. The point is that the alleged `dematerialization' is mostly mythical; computers are smaller but their numbers are enormously greater.

Referring again to larger question raised by the comments of Mr. Greenspan and Ms. Cairncross, it is difficult to decide exactly what categories of `final' products should be included in a meaningful comparison between (say) 1997, 1947 and 1897. It may well be the case that the mass of `final' food consumption per capita is about the same, or only slightly greater today than a century ago. However, meat and dairy consumption now are much higher, while (direct) grain consumption is much lower. Overall consumption, including consumption by animals, is therefore much higher today on a per capita basis. Moreover, per capita consumption of packaging materials is vastly higher today than in either of the two earlier periods.

Per capita consumption of rail transport in 1987 was considerably higher than today, but the reverse is true for motor vehicles and air transport. More important, the fuel consumed oer capita for all transportation purposes has increased enormously in the past century, and in the last half century. Similarly, the fuel consumed to generate electric power has increased enormously. A century ago, electric power was only available in big cities and it was still an expensive luxury. Today it is regarded as a necessity. Obviously there have been substantial improvements in the efficiency of gasoline engines, gas turbines and electric power generation, but these have been far outstripped by the increased demand.

Of course, apart from fuels and food, the total mass of materials consumed by the economy was — and still is — dominated by construction materials, especially sand, gravel and crushed stone. It is certainly true, as Greenspan notes, that technological improvements in the building sector permit some increase in the available floor space per unit of mass input. But, these efficiency gains are minor in effect, compared to the increased demand for floor space. So, even in this case, the quantity of building materials consumed per capita in the US has increased significantly in the last century.

It is certainly true, as both Greenspan and Cairncross note, that the materials produced today are worth more, in real terms, than a half century or a century ago. Quality and performance have improved in many areas. It is fair to say that more "information" is embodied in materials, and products, made nowadays than was the case in the past. On the other hand, it is easy to demonstrate that the total mass of materials processed — and wasted — has nonetheless increased enormously over that same time span.

Evidently, micro-miniaturization and other trends in the `high tech' sector have not, and probably will not, achieve significant dematerialization of the economy as a whole.

Growth, depreciation and technological change

All models of economic growth assume a production function whose arguments are tangible capital (K) and labor (L). More recently energy E and materials M have been included by some modelers, notably Jorgenson and his colleagues. Because it is difficult to measure capital stock directly, either in monetary or physical terms, it is assumed that capital accumulation is determined by the integral over time of investment (usually equated with savings) less depreciation. The rate of real depreciation is also difficult to measure, as already noted. In corporate accounts it is defined rather arbitrarily by the tax authorities (or the legislature) for purposes of calculating the fraction of earnings that can be retained free of corporate income tax to reinvest. In national accounts the so-called `capital allowance' — currently around 10 percent of GNP — is the sum of all such tax-sheltered earnings. (It is allowable depreciation, rather than savings by householders, that is the major — almost the only — source of investment into the corporate sector of the economy).

While the rate of depreciation of tangible physical capital is impossible to measure accurately and difficult to estimate even at the micro-level, aggregate depreciation is evidently a real loss to the economy. An asset that depreciates in a day is no asset at all. An asset that *appreciates*, such as an orchard or a vineyard or a growing forest, or an old master, or stock in a growth company, or land in a city center, is best of all. But the main point to be made here is this: the greater the real rate of depreciation the less the real rate of economic growth, *ceteris paribus*. (Depreciation of man-made capital assets is also a source of material waste and environmental pollution.) A second interesting point is that most natural assets *do not* depreciate when left undisturbed by man. If they depreciate, like topsoil, forests, fisheries, biodiversity or mineral reserves, it is because of human activity. Moreover, produced tangible assets, like buildings, equipment or infrastructure, invariably depreciate at some rate and must be replaced at some rate by human activity, whereas natural assets (other than mineral resources) may replace themselves. It follows that the more national income is based on man-made assets, the greater the fraction of national income that must be reserved for replacing those assets.

In fact, the US economic growth rate, in conventional GNP terms, has declined markedly since 1973. The average from 1947 to 1973 was 2.85 percent per annum. From 1973 through 1992 it averaged only 1.1 percent per annum.[6] (Since then it has bounced back up to around 2 percent but nobody knows how long the current boom can continue). To be sure, there are several competing theories to explain the growth slowdown, no single one of which is generally accepted.[7] Given the general confusion about causes, it is not unreasonable to suggest that part of the observed decline can be traced to accelerating depreciation — and thus a reduced rate of real tangible capital accumulation — across the whole economy.

There is anecdotal evidence suggesting that the average rate of depreciation of tangible capital equipment may have increased significantly over the last century. The most important components of productive capital in 1900 were long-lived structures, railroads (including rolling stock), bridges, canals, harbors, tunnels, dams and mines. A 50-year lifetime, corresponding to 2 percent annual depreciation, was not an unreasonable assumption for economists to make.[8] Today many business structures are designed and built for replacement after 20-30 years, railroads have been largely supplanted by highways and trucks (with 10-15 year lifetimes) and more and more investment is going into computers, information processing equipment and software — 35 percent by some estimates — with even shorter (3-5 year) useful lifetimes. It is hard to estimate the average, but 20 years (5 percent depreciation) might even be conservative for today's economy.

Setting aside this interesting historical speculation, which might be worthy of some future researcher's attention, it is important to note that some kinds of depreciation are not even included in the national accounts, although they may qualify for tax exemption by extractive industries. This applies to exhaustible natural resources such as oil and gas, minerals deposits and forests. Owners are generally allowed to deduct a depreciation allowance from revenues before tax, even though the original resource cannot be recreated. In effect, the law assumes that profits from the sale of natural resources can be (and will be) reinvested in another sort of capital stock that is equally productive.

But there are still other depreciable environmental resources that do not qualify for depreciation allowances, either because of, or despite, the fact that they can neither be recreated or substituted for by man. Fisheries, topsoil and biodiversity are examples. Clean air, fresh water, the carbon, oxygen and nitrogen cycles, benign climate and the stratospheric ozone layer are others. These resources, too, are being depreciated at an accelerating rate.

The economy adds value to materials. It does so by refining, combining, shaping, forming, assembling, finishing and otherwise embodying information in them [e.g. Ayres 1994a, Chapter 9]. Some of this added value (i.e. embodied information) is lost each year, due to wear and tear (e.g. of shoes, tires, bearings, cutting tools), corrosion — largely due to pollutants such as NO_x and SO_2 — and to various natural processes. Cutting the rate of real depreciation in the economy (irrespective of "allowable" depreciation for tax purposes) would result in faster economic growth. A decrease in the capital depreciation rate (say, from 5 percent to 4 percent per annum) would automatically increase the rate of capital accumulation and thus the economic growth rate.

If promoting growth of real tangible wealth is our objective, it is worthwhile examining some of these depreciation mechanisms and searching for ways to reduce the loss of value-added. Thus, while the strategy of repair, re-use, renovation and remanufacturing is more labor intensive than mass production and replacement, it has a less obvious economic virtue of conserving value-added.

The question at the end of the first section can now be answered, at least in principle. One can imagine a set of technological changes that make it possible to accomplish two things. One of them is reduce the rate of depreciation — hence increase the rate of accumulation — of tangible produced wealth (consisting of durable material goods). The second part of this strategy must be to cut down sharply on the use of inherently dissipative materials, especially hydrocarbon fuels. This is the primary strategy for reducing the environmental impact of economic growth, because most of the chemically active non-structural materials extracted and processed by the economy, as it now operates, are actually dissipative. This means they are converted into wastes as soon as they are used.

The second part of the overall strategy is relatively familiar in the environmental literature. It is a major part of what is often called "clean" or "non-waste" technology or "pollution reduction", all of which concern process change to reduce wastes and pollution. The substitution of non-polluting energy sources (such as wind or solar power) would be obvious examples. The first part of the strategy, however, is the one that permits tangible wealth to continue to accumulate even as materials flux and pollution are reduced. The objective must be to conserve value-added by renovation and remanufacturing of durable goods, which are the only material products that truly constitute wealth (by generating immaterial services to final consumers).

To summarize the two intertwined themes of the preceding discussion: (1) to achieve economic development and environmental salvation requires radical `dematerialization' of the economy; and (2) this strategy has two fundamental material-related elements, viz. *repair, re-use, renovation and remanufacturing* and *elimination of dissipative intermediates* (especially fossil fuels) to the maximum possible extent. The economics of the first part of the dual strategy have been discussed qualitatively: namely *conservation of value-added* (to permit growth without relying on economies of scale in mass production). There is a clear need for much more theoretical modelling and empirical work to clarify the issues, of course.

The question now arises: is it possible to achieve the second part of this dual strategy without unacceptable economic costs? Or even at negative cost? The answer depends on whether the necessary technological evolution — away from hydrocarbon-dependence — will occur automatically in response to current market forces or not. If market forces are *not* likely to be effective in the near term (due to well-known market failures and externalities), the answer turns on whether there exists a significant potential for "free lunches" and "double dividends". If the economy truly is on an equilibrium growth trajectory, in the sense that

R&D and other investments are now close to optimal — in terms of the existing markets — then only a major (and unlikely) change in the political climate will suffice to bring about the necessary changes. This issue is extremely controversial, of course, because it raises fundamental questions about widely used neo-classical economic models.

On economic disequilibrium and free lunch[9]

To restate the two questions at issue: is there any hope that non-carbon energy technologies can replace carbon-based technologies *without* interference by government? And, if not, is there any hope that such interference could be economically beneficial and growth enhancing (as well as environmentally necessary). Or must we assume, as the US Congress does, that cutting carbon consumption will necessarily be growth-inhibiting? Needless to say, this belief has been strongly influenced by lobbyists supported by a number of economists using long-term general equilibrium models that, in turn, assume that the economy is already on an optimal growth path.[10] It follows automatically, from this assumption alone, that any interference by government must *ipso facto* reduce option-space and thus be growth-inhibiting.

As regards the first question, it is clear that most of the indicators point in the wrong direction. The carbon-based energy industry is extremely well entrenched and it has all the advantages of scale, experience and political influence. Alternative technologies may eventually have their day, but the process will take many decades unless it is accelerated by government policy. As regards the second question, however, economists have had a strong influence on the politics. Moreover, the economic models on which policy advice is being given are based on a very questionable set of assumptions. I claim that these assumptions have not received adequate scrutiny.

This issue has recently been clarified by several papers that address the problem in terms of induced technological change (ITC) and "crowding out" [Grubb *et al* 1995; Goulder & Schneider 1996]. The latter authors acknowledge that the gross costs of CO_2 reduction policies based on ITC depend on whether or not there are "serious prior inefficiencies in the R&D market". This issue is obviously crucial to the conclusion.

It is well-known that a number of "bottom up" (engineering) studies have claimed the existence of very large opportunities for cost saving while cutting energy consumption — known as "free lunches" or "double dividends". These studies give many examples, together with detailed explanations (in many cases) of the barriers preventing their adoption. See, especially [Lovins & Lovins 1981, 1997; Krause *et al* 1992, 1993; Ayres 1994b]. It is also well-known that most economists have not taken these claims very seriously. They are routinely dismissed on the (theoretical) argument that `if such opportunities really existed, they would be exploited by cost-minimizing entrepreneurs'. The fact that this has not occurred is usually explained in terms of "hidden costs", although the origin of such costs, and the possibility of other plausible institutional reasons why firms might not take advantage of such opportunities, has not been tested empirically. Clearly economic statistics cannot throw much light on the matter. This subject is one that deserves more serious attention, especially in business schools.

The other way to approach the question is to seek evidence of the extent to which R&D investment is related to returns. In principle, technologies with a recent history of rapid cost reduction are the ones offering high returns, and should therefore attract the most investment. Conversely, technologies with a recent history of negative returns (cost increases) should discourage investment. Thus, it is curious that in the energy field, the technology that has long attracted the bulk of government investment is nuclear power, although the recent returns appear to be zero or negative. The other large past consumer of government R&D funding has been coal gasification and shale liquefaction. Both have failed economically. Meanwhile wind power and photovoltaic power — both of which are non-carbon based energy technologies — have demonstrated radical and continuing cost reductions with minimal R&D investment. At first glance, this suggests that the R&D market is indeed very inefficient and casts doubt on the viability of the "crowding out" hypothesis.

Obviously, the whole subject needs much more (and more open-minded) attention from economists. Admittedly, reliable data on returns to R&D are difficult to obtain, but this should not excuse lack of effort.

In my own view, there is sufficient and sufficiently strong historical evidence to support the thesis that reducing option-space — far from reducing the rate of productivity increase — can have, and frequently has had a very positive impact on economic growth. I believe, in short, that "necessity is (indeed) the mother of invention'. And when the invention (or innovation) is a radical one, in Schumpeter's sense, it can have enormous consequences in terms of opening up many new possibilities. This is not the place to discuss the point in great detail (it would require a book-length monograph) but a few examples should at least make the important point that the "induced technology" thesis is not trivial.

- The closing of the traditional near-eastern trade routes to the East, resulting from the rise of the Ottoman Turks, led Portugal and then Spain to develop long-distance navigational technologies that shifted the balance of power in Europe and resulted in the discovery and exploitation of the "new world" in the western hemisphere.
- A domestic shortage of charcoal in the early 18th century — due to deforestation for purposes of ship-building — induced British iron smelters to try (cheaper) coal as a fuel. Within a century the British iron industry had replaced Sweden, where charcoal was plentiful, as the world leader.
- The high cost of animal feed induced some British coal miners to try Newcomen's idea for using steam (from coal) to pump water out of mines, instead of horses. Success led on to Watt's stationary steam engine and thence to Trevithick's and Evans' engines on wheels and tracks and finally to Stevenson's `Rocket' and the railway age.
- The high cost and prospective shortage of whale oil (due to the disappearance of whales from nearby seas) induced a group of investors to finance the search for an alternative source of `illuminating oil' in the 1840s. The result was `Colonel' Drake's first oil well in Pennsylvania, soon followed by refineries, pipelines and a host of new applications of refinery by-products. The most important new application was the gasoline-burning mobile internal combustion engine developed by Gottlieb Daimler (based on Karl Otto's stationary gas engine) and gave Germany a major share of the world's largest industry.
- The shortage (and high cost) of skilled labor in the US led to the development of the so-called `American system' of manufacturing in New England — which eventually made the US the world's most productive manufacturing nation. The scarcity of farm labor in the American Midwest led to the development and adoption of machines for harvesting, and later for many other farm tasks. The scarcity of domestic labor in farmer's kitchens led, similarly, to the development of a host of labor-saving domestic appliances from washing-machines to vacuum cleaners.
- The 19th century British monopoly on trade with India gave British textile weavers a cheap source of popular vegetable dyes, such as indigo. The British monopoly on trade with Chile, the world's only source of natural nitrates, gave British farmers and munitions-makers a cheap source of fertilizer and explosives. Germany, which needed fertilizers and explosives (for munitions) invested heavily in synthetic dyes (from coal

tar) and synthetic ammonia. The success of these investments gave Germany the world's dominant chemical industry.

- The Japanese conquest in 1942 of Malaysia and Indochina, where most natural rubber plantations were located, greatly accelerated the development of synthetic rubber by the US, during World War II.
- The extreme scarcity of land for warehouses in Japanese cities led Toyota to develop the `just in time' process which made Toyota the world's most successful automobile manufacturer.

Hopefully this list is long enough to make the point. It is true enough that not every major technological innovation can be traced to a real shortage. The telephone and the electric light exploited latent, rather than actual, demand. They did not replace a direct competitor. However, I strongly believe that serious efforts to limit the output of CO_2 would actually be quite beneficial, in that they would accelerate the introduction of photovoltaic (PV) and hydrogen-based energy technologies that are known to be technically feasible but are (currently) rather far from economic competitiveness [Ayres & Axtell 1996 ; Ayres & Frankl 1998]. However this, too, is a topic that leads well beyond the limited scope of the present paper.

Conclusions

It is difficult to conclude a paper such as this. I have touched on a number of important economic issues that also clearly fall within the domain of industrial ecology. From the economic point of view, the most important new idea may be that changing times requires new growth models based on more sophisticated theory. Certainly the new growth theory must adequately reflect the importance of declining energy/raw materials costs as drivers of past growth. The theory must also enhance our detailed understanding of the implications of the approaching end of this era, notably the fact that future growth must depend increasingly on conservation of value-added and reduction of depreciation losses. The substitute for declining energy/raw material costs, as an `engine' of growth must be accelerated technological change in other areas, perhaps based largely on information technology.

From the industrial ecology perspective, the major messages of this paper must be two-fold. First, it is important to recognize a kind of `master equation', namely that depreciation equals waste and waste equals pollution. The second contribution of an IE perspective is that value-added conservation specifically means extended product life, enhanced recovery, renovation and remanufacturing of durables. It also implies gradual elimination of industrial processes involving dissipation of intermediates, *especially* combustion of fossil fuels.

Clearly there are a number of specific issues requiring both theoretical and empirical work by economists and engineers (in the broad sense) working together.

References

[Adriaanse *et al* 1997] Adriaanse, Albert, Stefan Bringezu, Allen Hammond, Yuichi Moriguchi, Eric Rodenburg, Donald Rogich & Hemut Schütz, *Resource Flows: The Material Basis of Industrial Economies* (ISBN 1-56973-209-4), World Resources Institute, Washington DC, with Wuppertal Institute, Germany, National Ministry of Housing., Netherlands & National Institute for Environmental Studies, Japan, 1997.

[Ahmad *et al* 1990] Ahmad, Yussuf J., Saleh el-Sarafy & Ernst Lutz (eds), *Environmental Accounting for Sustainable Development*, World Bank, Washington DC, 1990.

[Ayres 1989] Ayres, Robert U. ``Industrial Metabolism", in: Ausubel, Jesse & Hedy E. Sladovich(eds), *Technology & Environment*, National Academy Press, Washington DC, 1989.

[Ayres-d 1989] Ayres, Robert U., ``Industrial Metabolism & Global Change", *International Social Science Journal* **121**, 1989. (UNESCO, Paris - also translated into French & Spanish)

[Ayres-c 1994] Ayres, Robert U., ``On Economic Disequilibrium & Free Lunch", *Environmental & Resource Economics* **4**, 1994 :435-454. (Also INSEAD Working Paper 93/45/EPS)

[Ayres & Axtell 1996] Ayres, Robert U. & Robert Axtell, ``Foresight as a Survival Characteristic: When (if ever) Does the Long View Pay?", *Journal of Technological Forecasting & Social Change* **51**(1), 1996. (Also INSEAD Working Paper 93/83/EPS)

[Ayres & Frankl 1998] Ayres, Robert U. & Paolo Frankl, ``The Spaceship Economy", *Environmental Science & Technology*, forthcoming 1998.

[Ayres & Kneese 1969] Ayres, Robert U. & Allan V. Kneese, ``Production, Consumption & Externalities", *American Economic Review*, June 1969. (AERE `Publication of Enduring Quality' Award, 1990)

[Ayres & Masini 1996] Ayres, Robert U. & Andrea Masini, *An Application of Exergy Accounting to Four Basic Metal Industries*, Working Paper (96/65/EPS), INSEAD, Fontainebleau, France, September 1996.

[Azar 1996] Azar, Christian, *Technological Change & the Long-Run Cost of Reducing CO2 Emissions*, Working Paper (96/84/EPS), INSEAD, Fontainebleau, France, July 1996.

[Barnett & Morse 1962] Barnett, Harold J. & Chandler Morse, *Scarcity & Growth: The Economics of Resource Scarcity*, Johns Hopkins University Press, Baltimore, 1962.

[Bolch 1980] Bolch, William E. Jr. ``Solid Waste & Trace Element Impacts", in: Green, Alex E. S.(ed), *Coal Burning Issues*, Chapter 12 :231-248, University Presses of Florida, Gainesville FL, 1980.

[Davis *et al* 1971] Davis, W. E, *National Inventory of Sources & Emissions: Mercury, 1968*, (APTD-1510), W. E. Davis & Associates, Leawood, KS, September 1971. (for EPA, Research Triangle Park, NC)

[Davis-Cu 1972] Davis, W. E, *National Inventory of Sources & Emissions: Barium, Boron, Copper, Selenium & Zinc 1969- Copper, Section III*, (APTD-1129), W. E. Davis & Associates, Leawood, KS, April 1972. (for EPA, Research Triangle Park, NC)

[Davis-Zn 1972] Davis, W. E., *National Inventory of Sources & Emissions: Barium, Boron, Copper, Selenium & Zinc 1969- Zinc, Section V*, (APTD-1139), W. E. Davis & Associates, Leawood, KS, May 1972. (for EPA, Research Triangle Park, NC)

[Forrest & Szekely 1991] Forrest, David & Julian Szekely, ``Global Warming & the Primary Metals Industry", *Journal of Metallurgy* **43**(ISSN 1047-4838), December 1991 :23-30.

[Gaines 1980] Gaines, Linda L., *Energy & Material Flows in the Copper Industry*, Technical Memo, Argonne National Laboratory, Argonne IL, 1980. (Prepared for the United States Department of Energy)

[Georgescu-Roegen 1979] Georgescu-Roegen, Nicholas, ``Myths About Energy & Matter", *Growth & Change* **10**(1), 1979.

[Goulder & Schneider 1996] Goulder, Lawrence H. & Stephen H. Schneider, *Induced Technological Change, Crowding Out, & the Attractiveness of CO2 Emissions Abatement*, Draft, Institute for International Studies, Stanford University, Palo Alto CA, October 1996.

[Grubb *et al* 1995] Grubb, Michael, T. Chapuis & M. Ha Duong, ``The Economics of Changing Course: Implications of Adaptability & Inertia for Optimal Climate Policy", *Energy Policy* **23**(4/5), 1995 :417-432.

[Hueting 1980] Hueting, Rofie, *New Scarcity & Economic Growth: More Welfare through Less Production?*, North Holland, Amsterdam, 1980.

[Krause *et al* 1992] Krause, Florentin, W. Bach & Jonathan Kooney, *Energy Policy in the Greenhouse*, Earthscan, London, 1992.

[Krause *et al* 1993] Krause, Florentin, with Eric Haites, Richard Howarth & Jonathan Koomey. ``Cutting Carbon Emissions: Burden or Benefit? The Economics of Energy-Tax & Non-Price Policies", in: *Energy Policy in the Greenhouse* **2; part 1**, International Project for Sustainable Energy Paths, El Cerrito CA, 1993.

[Lovins & Lovins 1981] Lovins, Amory B. & L. Hunter Lovins, *Energy/War: Breaking the Nuclear Link*, Harper & Row, New York, 1981.

[Lovins & Lovins 1997] Lovins, Amory B. & L. Hunter Lovins. *Climate: Making Sense & Making Money*, Rocky Mountain Institute, Snowmass CO, November 13, 1997.

[Lowenbach *et al* 1979] Lowenbach, William A. & Joyce S. Schlesinger, *Arsenic: A Preliminary Materials Balance*, (EPA-560/6-79-005), Lowenbach & Schlesinger Associates, Inc., McLean, VA, March 1979. (for EPA, Washington, DC)

[Lübkert *et al* 1991] Lübkert, Barbara, Y. Virtanen, M. Muhlberger, I. Ingham, B. Vallance & S. Alber, *Life Cycle Analysis: International Database for Ecoprofile Analysis (IDEA)*, Working paper (WP-91-30), International Institute for Applied Systems Analysis, Laxenburg, Austria, 1991.

[McElroy & Shobe 1980] McElroy, A. D. & F. D. Shobe, *Source Category Survey: Secondary Zinc Smelting & Refining Industry*, (EPA-450/3-80-012), Midwest Research Inst., Kansas City, MO, May 1980. (for EPA, Research Triangle Park, NC)

[Parsons 1977] Radian Corporation, *Industrial Process Profiles for Environmental Use: Primary Aluminum Industry*, (PB281-491, EPA-600/2-77-023y), Radian Corporation, Austin TX, February 1977. (for IERL, Cincinnati, OH)

[Potter & Christy 1968] Potter, Neal & Francis T. Christy, Jr., *Trends in Natural Resource Commodities*, Johns Hopkins University Press, Baltimore, 1968.

[Repetto 1992] Repetto, Robert, ``Accounting for Environmental Assets", *Scientific American*, June 1992 :64-70.

[Repetto & Magrath 1989] Repetto, Robert & William D. Magrath, *Wasting Assets: Natural Resources in the National Income Accounts*, World Resources Institute, Washington DC, 1989.

[Sichel 1997] Sichel, Daniel E., *The Computer Revolution* (ISBN 0-8157-7896-1), Brookings Institution Press, Washington DC, 1997.

[Smith 1979] Smith, V. Kerry (ed), *Scarcity & Growth Revisited*, Johns Hopkins University Press, Baltimore, 1979.

[Thomas 1977] Thomas, J. A. G., *Energy Analysis*, Westview Press, Boulder CO, 1977.

[von Weizsäcker *et al* 1994] von Weizsäcker, Ernst Ulrich, Amory B. Lovins & L. Hunter Lovins, *Faktor Vier* (ISBN 3-426-26877-9), Droemer Knaur, Munich, 1994.

[Watson & Brooks 1979] Watson, John W. & Kathryn J. Brooks, *A Review of Standards of Performance for New Stationary Sources-Secondary Lead Smelters*, (MTR-7871), MITRE Corp., McLean, VA, January 1979.

[Wolff 1995] Wolff, Edward N., ``Technological Change, Capital Accumulation, & Changing Trade Patterns Over the Long Term", *Structural Change & Economic Dynamics* **6**(1), March 1995 :43-70.

[Battelle 1975] Battelle - Columbus Laboratories, *Evaluation of the Theoretical Potential for Energy Conservation in 7 Basic Industries*, (PB-244-772), Battelle - Columbus Laboratories, Columbus OH, June 1975. (Prepared for U. S. Federal Energy Administration)

[PEDCo-Cu 1980] PEDCo-Environmental, *Industrial Process Profiles for Environmental Use: Primary Copper Industry*, (PB81-164915, EPA-600/2-80-170), PEDCo-Environmental, Cincinnati, OH, July 1980. (for IERL, Cincinnati, OH)

[PEDCo-Pb 1980] PEDCo-Environmental, *Industrial Process Profiles for Environmental Use: Primary Lead Industry*, (PB81-110926, EPA-600/2-80-168), PEDCo-Environmental, Cincinnati, OH, July 1980. (for IERL, Cincinnati, OH)

[USS 1971] McGannon, H. E. (ed), *The Making, Shaping & Treating of Steel*, United States Steel Corporation, Pittsburgh PA, 1971.

Endnotes

1. The long-term downward trend has been well-documented, especially by a number of studies conducted by Resources for the Futures Inc. [e.g. Barnett & Morse 1962; Potter & Christy 1968; Smith 1979]. However, exhaustion does happen. There is no tin or copper left to mine in Cornwall. For that matter, there is virtually nothing left worth mining anywhere in Western Europe. There is no petroleum left to pump from Western Pennsylvania or Ohio or Indiana or Southern California.

2. Financial wealth consists of money, marketable securities, partnerships, bank deposits, receivables, insurance policies, etc.

3. This problem, and some of its implications, have been pointed out by a number of authors e.g. [Hueting 1980; Repetto & Magrath 1989; Ahmad *et al* 1990].

4. For early attempts see, for example [Ayres & Kneese 1969; Ayres 1989]. A much more comprehensive study, for the years 1975-1994 has been carried out for the US, Germany, Japan and The Netherlands and published by the World Resources Institute under the title "Resource Flows: The Material Basis for Industrial Economies" [Adriaanse *et al* 1997].

5. The consumption of copper wire by the US electrical goods industry has risen by 250 percent since 1947. This represents a slightly lower rate of growth than most manufacturing industries. However, some copper wire has been replaced by aluminum (in 1983 1.2 MMT of copper wire was produced, along with 0.51 MMT of aluminum wire). Since that time aluminum use for electrical wiring has declined, but glass fiber usage for telecommunications has increased sharply, displacing some copper wire. However, while glass fibers can carry far more information per unit mass, the amount of copper displaced cannot be more than a few hundred thousand tons.

6. This decline has been termed `the Solow paradox' because of a published comment by Solow (c. 1989) to the effect that increasing investment in computers and software had not led to increased labor productivity. This `paradox' led to a major OECD conference [199?].

7. The four main contenders have been characterized as: (1) mismeasurement, (2) mismanagement, (3) diffusion delay and (4) `the capital stock theory'. The mismeasurement theory suggests that productivity has in fact improved, but that it does not show up in the statistics because much of it is hidden in product quality and performance. The mismanagement theory is that investment in information technology has in fact been a waste of money. The diffusion delay theory says that the economic benefits of information technology are real enough, but take a long time to be manifest in the productivity statistics. The capital stock theory is relevant: it says, in effect, that IT still constitutes a small percentage of total invested capital, (11.7 percent for all information processing equipment and only 2 percent for computers *per se* in 1993) mainly due to the fact that (i) large scale investment is still a relatively recent phenomenon, so accumulation is still not very large and (ii) both equipment and software depreciate much faster than conventional capital equipment and infrastructure [e.g. Sichel 1997].

8. For an instance, see [Wolff 1995].

9. The title of this section is taken from [Ayres 1994b].

10. For a comprehensive recent comprehensive survey of the models and their underlying assumptions, see [Azar 1996].

Table 1: NATIONAL WEALTH, BASED ON NATIONAL ACCOUNTS DATA, 1945-1992 (1987 $)

	1945	*1950*	*1955*	*1960*	*1965*	*1970*	*1975*	*1980*	*1985*	*1989*	*1990*	*1992*
1 Real estate, owner occupied (a)	554.4	838.8	1162.6	1413.5	1583.3	1882.9	2361.7	3348.3	3569.1	4254.1	4023.5	
2 Consumer durables	309.4	512.6	671.0	734.1	808.7	1016.5	1141.0	1329.5	1462.5	1764.9	1775.3	1817.7
3 Corporate equity (b)	746.7	633.4	1221.1	1499.0	2175.0	1984.8	1220.8	1517.8	1975.9	2387.0	2043.9	2984.9
4 Non-corporate business equity	1265.1	1351.1	1398.8	1468.6	1563.8	1564.6	1898.5	2655.4	2349.9	2403.6	2311.3	1845.8
5 Other equity (c)	1488.0	1103.6	1195.6	1344.1	1630.2	1911.7	2151.1	2423.9	3562.9	4549.5	4447.4	5117.0
6 Subtotal, tangible reproducible private wealth (d)	939.1	1449.8	1963.9	2319.1	2625.1	3186.9	3830.1	5050.7	5427.9	6441.0	6207.4	7763.9
7 Subtotal, private financial wealth	3499.8	3088.0	3815.5	4311.8	5368.9	5461.1	5270.4	6597.1	7888.6	9340.1	8802.6	9947.7
8 Total private wealth	4438.9	4537.8	5779.4	6630.8	7994.0	8647.9	9100.5	11647.9	13316.6	15781.0	15009.9	17711.6
9 Gov't tangible reproducible assets (e)						1873.0	2059.9	2206.8	2364.2	2582.8	2537.0	2587.0
10 Federal gov't net financial assets	-1495.3	-924.5	-865.0	-794.3	-775.3	-702.4	-755.7	-825.9	-1513.0	-2039.5	-2186.2	-2441.4
11 State & local gov't net financial assets	-5.4	-18.6	-90.0	-158.2	-192.4	-232.4	-182.5	-93.9	-63.2	-91.2	-110.5	-184.0
12 Subtotal gov't net financial assets	-1498.8	-941.3	-952.9	-950.0	-964.6	-931.6	-931.8	-910.7	-1567.1	-2120.5	-2286.9	-2590.1
13 Subtotal national wealth, excluding row 9	2940.1	3596.5	4826.5	5680.8	7029.4	7716.4	8168.6	10737.2	11749.5	13660.5	12723.0	15121.5
14 Total of above including row 9						9589.4	10228.5	12943.9	14113.7	16243.3		17708.5

a. including owned by non-profit institutions

b. Market value of securities, where available

c. Credit market instruments, life insurance and pension reserves, security credit and miscellaneous assets, net of liabilities

d. Includes wealth held by households and nonprofit institutions (e.g. churches, universities, foundations, etc.)

e. Including infrastructure, buildings, vehicles, military equipment, etc. Data from *Statistical Abstract of the U.S.*, 1991, Table 762.

TABLE 2: RECYCLING SAVINGS MULTIPLIERS (tons/ton product)

	Iron/steel	Aluminum	Copper	Lead	Zinc
Ore percent	*52.8% Fe*	*17.5% Al*	*0.6% Cu*	*9.3% Pb*	*6.2% Zn*
Major source	*[USS 1971]*	*[Parsons 1977]*	*[Gaines 1980]*	*[PEDCO-Pb 1980]*	*PEDCo-Zn 1980]*
Energy Used (gJ/t)	*22.4*	*256*	*120*	*30*	*37*
Water Flow in/out (t/t)	*79.3*	*10.5*	*605.6*	*122.5*	*36.0*
Material Inputs					
Air	1.9	0.3	1.6	4.4	5.8
Solids	17.3	11.0	612.1	126.2	55.8
Total Material Inputs	19.2	11.2	613.7	130.5	61.6
Material Outputs					
Product	0	0	0	0	0
Byproducts	0.2	0.1	1.0	6.7	4.9
Depleted air	1.5	0.2	1.3	1.2	2.4
CO_2	0.5	0.8	0.02	0.03	0.03
SO_X	0.01	0.06	1.47	0.005	0.01
Other gaseous material	1.18	0.002	0.15	0.28	0.03
Potential recycle	0.6		3.2	0.1	0.5
Overburden	12.5	0.6	395.4	72.5	37.3
Gangue	1.1	6.1	211.0	44.6	16.3
Other solid material	1.5	1.4	0.1	2.5	0.1
Sludges, liquids	0.1	1.9	0.1	2.6	0.1
Total Material Outputs	19.2	11.2	613.7	130.5	61.6

Notes:

Major byproducts include SO_2 used for sulfuric acid production and saleable offgas.

Depleted air = air from which all oxygen has been taken for combination with other materials.

Potential recycle includes slag, scrap etc. potentially usable in the process chain, but not used.

Overburden = That portion of solid material extracted during the mining process which is not part of the ore.

Gangue = That portion of the ore extracted during beneficiation which is not part of the concentrate.

Sludges and liquids do not include dilution water.

Source for aggregate energy values: [Forrest & Szekely 1991]. The materials/energy costs of producing this energy are not considered in this table.

Source for water flow values: [Lübkert et al 1991]

Source for overburden & gangue percentages: [Adriaanse et al 1997]

Other sources used: [Battelle 1975; Bolch 1980; Davis-Cu 1972; Davis-Zn 1972; Davis et al 1971; Forrest & Szekely 1991; Lowenbach et al 1979; Lübkert et al 1991; McElroy & Shobe 1980; Masini & Ayres 1996; PEDCo-Cu 1980; Thomas 1977; Watson & Brooks 1979]

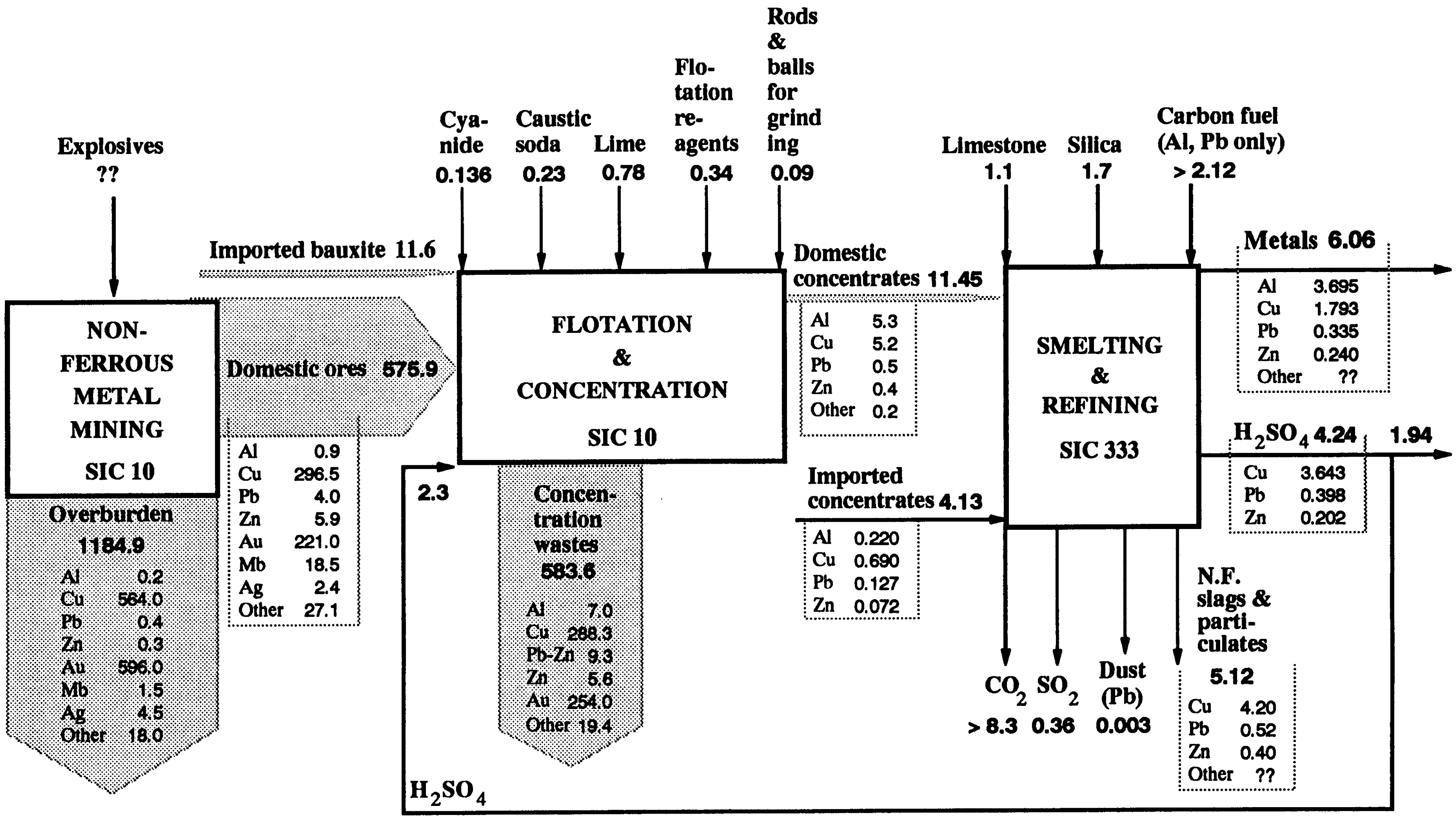

Figure 1 Mass flows in the US non-ferrous metals sector, 1993 (MMT)