"TOWARD A UNIVERSAL MEASURE OF ENVIRONMENTAL DISTURBANCE"

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May 1993

Prices should tell the ecological truth
Ernst-Ulrich von Weizsäcker

Abstract

In recent years the environment has increasingly been seen (and treated) as a collection of unrelated components or subsystems, rather than as an indivisible whole. This reductionist trend is dangerous. To counteract it, there is a need for simple, universal measures of the aggregate (direct and indirect) environmental disturbance associated with any given economic activity or product. Three candidates are discussed; energy flux, materials flux, and entropy flux. No single measure can be selected, in practice, on the basis of *a priori* considerations alone, although theory suggests that entropy flux would be the most comprehensive. It will be necessary to gather a great deal of data and compare the alternative measures in a number of specific applications. However, one significant insight arising from preliminary work is that the importance of materials fluxes has been seriously underestimated. Consequently, a clear goal of government policy and business stategy should be to increase the economic productivity of materials; i.e. to encourage "dematerialization" of products and services.

Introduction

In the early 1970's many environmentalists, such as Paul Ehrlich [Ehrlich 1968] and Barry Commoner [Commoner 1971, 1976] tended to blame economic growth itself for pollution and environmental destruction. The Club of Rome's influential Report, *Limits to Growth* [Meadows *et al* 1972] was predicated on similar assumptions. They all argued that economic growth cannot occur without increasing use of energy — especially fossil fuels — and increasing use of minerals and other industrial materials.[1] In this set of assumptions (which we believe to be false) they agreed completely with their principal political and intellectual antagonists, the conservative industrial community, supported by most engineers and

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[1] Waste and pollution are inevitable accompaniments of extraction and use, as a consequence of the fundamental physical law of conservation of mass [Ayres & Kneese 1969].

mainstream economists. The environmental debate was, for more than a decade, mainly a public debate on economic growth itself. This reduced the practical scope of environmental protection to those incremental regulatory actions that could be justified within a more or less conventional economic policy framework. Even in recent years, many environmentalists (especially European Greens) have seemed to accept the "no growth" position, at least implicitly.

In 1986 the public debate began to shift away from the futile "growth vs. no growth" argument, as a result of the publication of the Report of the World Commission on Environment & Development [Brundtland 1987].[2] This commission had been created by the U.N. General Assembly to address the growing perception that environmental problems in the industrial world cannot be solved as long as the "Third World" is impoverished. In the first place, it is now widely agreed that population growth is one of the major root causes of the environmental crisis. But human fertility control cannot be achieved by fiat. In fact, progress in this area will require universal education, improvements in the status of women, and improved economic prospects. Deforestation, to take another example, cannot realistically be controlled as long as impoverished peasants have no other source of fuel for their own cooking fires, nor any better source of income (from selling firewood or charcoal in the towns). It is no less true for being a political slogan that "poverty is pollution".

In a way, the WCED Report and the ensuing public debate, leading up to the Rio Conference in June 1992 brings us back to the "growth vs. environment argument, but from a different point of view. It is now much clearer that if the choice is between "growth" on the one hand and environmental protection, on the other, the choice of the vast majority of mankind is unambiguously for growth. If these are truly the only options we have, there is little reason to hope for a favorable outcome.[3] As Madame Pompadour, mistress to King Louis XV of France, said: "Après nous, le déluge".

There are some technological optimists, however, (among which group we include ourselves) who believe that there is a third possibility. We believe, in fact, that if technology is properly mobilized by committed world governments, the apparent "link" between energy and materials consumption and economic growth can be broken, or shown to be chimerical. There are already signs that the link was never as strong as some economists and engineers argued in the early 1970's. Energy consumption per unit GDP has been declining for the last two decades, more or less, and there are signs that materials consumption per unit of GDP may do likewise. We discuss these possibilities later.

Need for Holistic Systems Analysis

[2] The Commission has been widely referred to as the Brundtland Commission, because it was chaired by Gro Harlem Brundtland, then (and now) Prime Minister of Norway.

[3] In this case, one would have to hope that most of the scientists are wrong!

Since the early 1970's, the environmental movement has become increasingly professionalized and bureaucratized. As a consequence, largely, of the latter development, the "environment" is no longer seen in a holistic sense, but in terms of a number of specific, essentially independent issues. Nowadays, the "causes" of pollution are attributed, for the most part, to narrowly defined actions (or failures to act) of equally narrowly defined "polluters". The responsibilities for abatement or cleanup are correspondingly narrow. Solid wastes, hazardous or toxic wastes, liquid wastes and airborne wastes are likely to be allocated to different government departments, ranging from public health agencies to water/sewer authorities. Their regulatory powers are controlled by different kinds of legislation framed under different circumstances, sometimes based on quite different regulatory philosophies. The right hand does not know what the left hand is doing, and *vice versa*. Activities of different arms of the same agency can interfere with each other. (For instance, incineration can reduce the solid waste disposal problem and even produce useful energy as a by-product, but it creates an air pollution problem. On the other hand, to reduce the emissions of particulates and sulfur oxides from power plants creates solid wastes that must be disposed of somewhere on land. There is nobody with a global view of the problem to mediate among the parochial interests. There is nobody with the responsibility or the authority to induce competing offices, departments and bureaus to co-operate.

Yet the environment is, by its very nature, unsuited to incremental control strategies. It is equally unsuited for reductionist "bottom up" modes of analysis. The problem is that man's scientific insights are now, and will continue to be, insufficient for predicting the detailed environmental consequences of any change or perturbation. To take a concrete instance, nobody can predict the exact physiological effects of ingesting any chemical, still less the genetic or ecological consequences of its dispersion. This uncertainty is multiplied by the enormous number of different chemicals, materials, and mixtures simultaneously manufactured and used by man (natural and synthetic alike), not to mention the variety (type and intensity) of possible reaction modes, and interaction effects. Disregarding carcinogens and highly toxic or radioactive substances (which are without fail considered dangerous from a human health point of view and are therefore commonly placed under strict control, irrespective of whether ecological consequences are likely or not), only one important environmental problem has as yet been predicted in advance from the creation or displacement of any particular material stream. This single exception was Rowland's chance recognition of the highly specific reactive potential of the CFCs at high altitudes.

In speaking of the environment it is literally true that "everything depends upon everything else". A holistic "top down" perspective is essential to identifying the most important underlying factors and relationships. It is equally important to adopt a very broad perspective for seeking and — hopefully — finding effective global strategies to save the planet.

Holistic analysis presupposes that it is possible to classify variables by degree of importance and derive significant and defensible results by judicious simplification. A universal measure to estimate and compare the relative environmental impact of different activities, goods, services and regulatory policies would be of great value.

Such a measure should satisfy the following conditions:

- It should be based on measurable quantities;
- It should relate to the most significant environmental impact potentials of human activities;
- It should allow transparent, cost-efficient and reproducible estimates of the environmental impact potentials of all kinds of plans, processes, goods, and services;
- It must be applicable on the global level.

Choosing a single indicator to compare the environmental impact intensities of all kinds of present and future processes, goods, and services might seem to be a daring step, precisely because it constitutes a vast reduction of complexity. Simplification cannot be proven to be "correct" in scientific terms. Only its plausibility in a variety of circumstances can be established.

But agreeing on the common use of simple and crude measure is nothing new in the real world. The gross domestic product (GDP) has been used for decades as a measure of "welfare" despite serious doubts that it really measures any such thing. It omits important sectors, including subsistence agriculture and unpaid household work (mostly by women), and it omits environmental services. On the other hand, it includes dubious items, like "defensive measures" to protect health and safety, despite the fact that the health and safety hazards result from human activity in the first place. Clearly defensive expenditures make no contribution to net social welfare. In fact, environmental statisticians and economists such as Rofie Hueting of the Netherlands [Hueting 1980], Robert Repetto of the World Resources Institute [Repetto 1985, 1990] and Herman Daly of the World Bank [Daly & Cobb 1989] have been very critical of the use of GDP as a measure of relative welfare for these reasons. Nevertheless, GDP is still being used by macro-economists, almost universally, without any of the adjustments or corrections that critics advocate.

"Net Energy" as a Universal Measure

Perhaps the most obvious of all candidates for a single measure is energy (or, more accurately "free energy") flux. Underlying this is the notion that energy is the "ultimate resource" and thus the most important measure for both human and ecological activity. The idea that Darwinian evolution might be driven by the competitive search for sources of metabolic energy was propounded in the 19th century by the Austrian physicist Ludwig Boltzmann. This idea was further developed by Alfred J. Lotka, the founder of biophysics. Lotka proposed "free energy maximization" as an evolutionary principle [Lotka 1922].In modem form, the notion that energy stocks and flows are they key determinants of ecological systems was rediscovered and elaborated by Howard Odum [Odum 1971].

A few years later, a formal methodology for project analysis was proposed by several investigators [Chapman 1974; Herendeen & Bullard 1974; Hannon 1975; Leach 1975; Slesser 1975]. This became known as "net energy analysis". The basic idea was that alternative energy production schemes (and, by implication, other processes and products) could be evaluated by careful comparison of direct and indirect energy inputs and outputs. For instance, in comparing nuclear power plants with ethanol from corn, or solar power satellites, it is clearly important to take into account the energy required to produce and maintain the capital equipment. The broader implications of this sort of analysis were discussed (and criticized) widely in several scientific meetings and journal articles between 1975 and 1981.[4] Net energy analysis was used in the late 1970's as a formal project evaluation tool by the U.S. Department of Energy.

However, net energy analysis was ultimately (and perhaps even unfairly) criticized and discredited by economists as "an energy theory of value". Economists tend to argue that there is only one consistent measure of value — money — and that the use of energy (or any other measure) as a substitute for monetary value is inconsistent and unjustified. To allay suspicion and put the following discussion into perspective, we explicitly accept this position, in principle.

However, there is one important *caveat.* We agree that monetary value should be the only acceptable measure of societal value, *provided* there exists an impersonal mechanism (i.e. a free and "perfect" competitive market) for determining prices. If the market is imperfect and there are significant externalities (i.e. unpaid social or environmental costs) then the market price can be virtually irrelevant.

In the case of energy, as it happens, significant unpaid costs do exist, and market prices are certainly not reliable measures of societal value.[5] This fact could well be the basis for reconsidering the use of net energy analysis in appropriate circumstances. However, as a measure of gross environmental impact, there are objections to exclusive reliance on an energy measure. we will propose a somewhat more comprehensive alternative, below. In any case, net energy analysis in the original version has few, if any, influential adherents today.

Aggregate Material Fluxes as a Measure of Environmental Impact

We noted above that two decades ago most industrialists, supported by many engineers and economists, assumed (many still assume) a very tight link between economic activity and materials use. Evidence for this perceived link goes back at least to the first industrial revolution (c. 1800). Most anthropogenic material flows have been growing exponentially, since then, outpacing by far the growth of the human population. Such man-moved material flows include: plowed soil, building materials, earth movements for construction, mining overburdens, erosions, dredgings, sand, minerals, water (hydropower, irrigation, process, drinking), oil, natural gas, coal, industrial–, agricultural–, natural–, and forestry products (including international trade), CO_2, SO_2, and all kinds of emissions, effluents, and "waste".

[4] Major references are [Gilliland 1975; Long 1975; Huettner 1976; Berry *et al* 1978; Alessio 1981; Hertzmark 1981; Huettner 1981].

[5] For recent studies, see [Grupp 1986; Hohmeyer 1988; Krupnick 1990; Hubbard 1991].

Material displacements are among the most fundamental causes of damage to nature attributable to man's activities.[6] These fluxes already have well-established regional consequences; many have global consequences. In some cases anthropogenic fluxes rival geological fluxes in magnitude [Brown *et al* 1992]. By comparison, human energy "consumption" is essentially inconsequential in comparison to the natural solar flux. Even the winds, tides, rainfall and other natural phenomena may "consume" much more energy than human activities. However, the material fluxes put in motion by man simply to capture and utilize energy from natural sources, from running water to coal-fired electric power plants or liquid fuels used for transport purposes (including waste emissions such as CO_2, SO_2, NO_x) are considerable.

The buffering capacity of the ecosphere for anthropogenic material fluxes is now approaching limits, as pervasive environmental problems testify. It can be argued with some cogency that the high "material intensity" (or, its obverse, low resource productivity), of current western products and services de-stabilizes the ecosphere. The environmental problems associated with planned and command economies have been even more severe. Contrary to the major thesis of *Limits to Growth* [Meadows *et al* 1972], one could argue that it is not the availability of resources that limits global economic growth but the ecological consequences of man-induced material fluxes. Unless "business as usual" in the industrial countries gives way to radical new approaches, the resulting stresses to the ecosphere will lead to ever more violent and unpredictable responses.

As a consequence, human civilization, as we know it, will be maintainable only by increasingly drastic (and costly) intervention as natural processes go awry. Survival itself will become a costly defensive battle against increasingly frequent and severe man-created ecological disasters. The richer nations, i.e. those that have accumulated material wealth in the past (partly at the expense of the ecosphere) will be in a better position for a while to engage defensive or passive measures in order to protect their citizens against an increasingly hostile environment. The development of the Third World and the formerly communist countries by maximum exploitation of extractive raw materials (such as low quality coal) could well be characterized as a policy of "strength through exhaustion". It could even be characterized, more harshly, as a blueprint for suicide of the rich, if not global genocide. Goods and services must therefore be "de-materialized" – on a "cradle to grave" basis.

We suggest that the material handled or moved per unit of service delivered (MIPS) reflects a considerable range of environmental impacts. This simple measure therefore allows the comparison of certain functionally equivalent economic outputs from an ecological point of view [Schmidt-Bleek & Wohlmeyer 1991]. When developing plans or designing new services, products or infrastructures, and when considering future environmental legislation and international agreements, the primary goal would have to be moving toward life-cycle-wide de-materialized goods and services. *In short: a sustainable economy is necessarily a*

[6] The observation that waste residuals are inherently associated with extractive economic activity goes back at least to the 1960's, viz. [Ayres & Kneese 1969]. For more recent literature, see [Ayres 1979; Ayres & Kneese 1989; Ayres 1989; Schmidt-Bleek 1992a,b; Ayres & Simonis 1993]

substantially de-materialized economy. "Consuming" Beethoven is probably better for the soul and safer for the body — and far more "ecological" — than driving motor-cycles.

Clearly, however, there are objections to exclusive reliance on materials displaced as a measure of environmental impact. To state an obvious objection: in some cases high-energy processes may involve less material than low energy processes. Moreover, there are substantial differences in the "eco-toxic" potential of different anthropogenic material streams. Surely displacing sand or soil (or water) is far less dangerous to the environment, per unit mass moved, than the emission of plutonium, CFC's or dioxins to the atmosphere, or PCB's or mercury to the rivers. Surely the emission of some virulent micro-organism lethal to a major food crop, such as rice or wheat — perhaps a plant pathogen equivalent of the AIDS virus — would have far more damaging environmental impact than almost anything one else imaginable. Yet virtually no mass need be displaced. Similarly, it is possible to wipe out the last breeding members of a threatened species (and thus reduce biodiversity) without moving any mass at all.

For these reasons, either alternative or additional generic measures for the environmental impact intensities should be considered. Without further ado, we argue below that both energy intensity and materials intensity are good measures of some aspects of environmental impact. However, neither is sufficient.

Entropy as a Measure of Environmental Disturbance

From an abstract theoretical perspective, the most attractive single measure of environmental impact of a process or action is *entropy*. To be more precise, the impact measure would be total entropy S created (or "negentropy" used up) by that process. For instance, if the "process" under consideration is extraction and use of some resource, the entropy produced reflects both the physical mixing of materials that results from the concentration phase of the process and the loss of "available useful work" (free energy) resulting from the use of fuel for chemical processing that is needed to reduce an element from its compounds.

In comparing two possible processes to achieve the same result with equal monetary costs, one would *ceteris paribus* choose the one that involves the least entropy production. In comparing two products with equal monetary costs, again one would choose the one involving the least entropy production, taking into account the whole product life cycle. When monetary costs are different, it would be necessary to find a way to attach some social cost to entropy production, in monetary terms. If monetary costs are indeterminate, of course, the entropy measure would have to be used on its own.

The precise technical definition of entropy need not detain us here. It is sufficient to say that several equivalent definitions can be found in textbooks. The most familiar definition is the differential version: $\delta S = \delta Q/T$ for an irreversible thermal process, where the differential δS simply means a small change in entropy. Moreover, feasible methods of numerical calculation for most cases of practical importance can also be found in the textbooks. The actual calculations are not particularly difficult.

In the case of any fossil fuel, the stored chemical energy in the fuel is converted by combustion into heat, δQ, which accomplishes some "useful work". Eventually the waste heat is dissipated into the environment, and finally radiated into outer space, at the average temperature T of the earth (300°K). While the energy in the fuel is conserved, the "useful" portion is not. It is an exhaustible resource. Since the temperature at which waste heat is dissipated is essentially the same for every process, the entropy associated with fuel use is (almost) exactly proportional to the chemical energy content (BTU), or free energy, of the fuel.

Entropy can also be used as a means of comparing exhaustible mineral resources, both with each other, and with energy resources. The highest entropy state of the lithosphere (continental earth's crust) would be one in which all materials were uniformly mixed in a sort of "soup". The abundances of each element in such a mixture have been determined by geologists. It would consist of oxygen (47%), silicon (28%), aluminum (8%), iron (4.6%), calcium (4%), potassium (2.3%), sodium (2.2%), magnesium (1.8%), carbon (0.5%), titanium (0.4%), and everything else (0.72%). Except for aluminum, iron, magnesium and titanium, metals are quite scarce. For instance, copper is only 60 parts per million (ppm) in the earth's crust; zinc is 70 ppm, lead only 14 ppm, uranium 2.7 ppm, and gold .004 ppm.

By contrast, metal ores now being exploited are much richer, on the average, than the uniform lithospheric "soup" would be. In the cases of the more common metals, the ratios of ore grade to "soup" range from about 3 for aluminum to 10 for iron. However for the heavier metals we have ratios like 2350 (Pb), 800 (Au), 630 (Zn), and 150 (Cu). In other words, nature has helped us by leaving an endowment of highly concentrated ores. This high degree of concentration is equivalent to a natural endowment of *negentropy*; when this endowment is subsequently dissipated by human extraction and use, entropy is increased by a like amount.

As it happens, the quantitative calculation of entropy of mixing is quite straightforward. Entropy produced by dispersion is approximately inversely proportional to the natural logarithm of the abundance of the material in the "soup". The smaller the natural abundance the greater the (negative) logarithm. Evidently, the entropy penalty due to a dissipative use of virgin aluminum (from ore) is relatively small compared to the entropy penalty due to using virgin lead. The entropy penalty for dissipating lead is small, in turn, compared to the entropy penalty for dissipation of platinum or gold.

Note that there is a negentropy gain from the *physical* concentration of a low grade ore like copper, silver or gold into a high-grade concentrate. This must be paid for entropically, of course, by the use of energy and/or flotation chemicals and capital equipment. There is also a negentropy gain from *chemical* reduction of an ore mineral (usually an oxide) to the pure metal. The overall entropic cost of the purification process is proportional to the natural logarithm of the concentration ratio (the inverse of the ore grade), plus the chemical energy of the fuel used in smelting. However, the entropy cost of a *dissipative use* of the same material is much greater. It consists of two components: the logarithm of the inverse of the crustal abundance, and the chemical potential loss from spontaneous oxidation of the metal.

So far we have discussed *thermodynamic entropy* associated with fuel use and chemical reduction processes and *mixing entropy* associated with materials concentration and dispersion processes. There is another important contribution to entropy production in the industrial world: *information loss*.[7] We are not referring to lost library books or computer files, although those kinds of information losses are real and potentially significant. (When the library at Alexandria was destroyed a significant portion of the world's accumulated scientific knowledge went up in smoke). Nowadays, technical information is seldom actually lost, but books and papers deteriorate. Everybody who uses a computer knows that data, whether stored or moved, tends to be degraded over time. To compensate for this, a continuous process of copying, correcting and (in some cases) reconstruction is needed.

The same thing applies to information stored in complex shapes, such as industrial patterns, casting or stamping molds, gears, bearings, cutting tools, jigs and fixtures, templates, and the like. In time the sharp edges wear away, and the "message" being transmitted is garbled. This, too, is a loss of information. Wear and tear can be thought of as the production of entropy. (Increasing product life would decrease the rate of entropy production).

For biological organisms, the process of reproduction involves a transfer of information. If the information store (the chromosomes) is damaged, the offspring will not be viable. In a sense, reproduction is a self-correcting process of information transfer between generations. But, of course, there is a loss of genetic information when a species disappears. The entropic computations cannot be exact, at present, because there is considerable uncertainty about the actual information content of genetic material (much of the "information" is apparently redundant or non-functional). But, in principle, biologists could make reasonable estimates of the genetic information associated with biodiversity, and the corresponding information loss (= entropy production) due to reduced diversity.

Some Historical Notes

The fact that the "entropy-productivity" of natural resources is very low at present in comparison to that of labor or capital is largely due to the fact that the true extent of the environmental externalities has only recently been recognized. Of course, this is the reason for the fact that market prices do not "speak the ecological truth". The complete neglect of environmental damages during the communist regimes in eastern and central Europe was paralleled by state subsidies that maintained extractive resource prices in these countries even lower than in the west. In point of fact, the centrally planned "command" economies of the former COMECON countries created even larger energy and material flows per service unit (and, in some cases, even per capita) than the countries of the west [Schmidt-Bleek 1991].

The markets as they exist today, even in western countries, cannot internalize all of the environmental costs imposed by industrial man. Therefore man must design appropriate

[7] The equivalence of information (in the technical sense) with negative entropy goes back to the discussions of "Maxwell's Demon" in the 1920's and 1930's. The connection was further developed by the French physicist Leon Brillouin [Brillouin 1950, 1953]; it was further utilized by Claude Shannon in his development of the formal mathematical theory of communication [Shannon 1948].

"second best" regulatory mechanisms, through government intervention, if he wishes to continue economic development while minimizing disturbances to the ecosphere. Experiences gained in the west with long-term wage increases for labor, during the second half of last century and since then, have shown that sectoral cost adjustments can adapt to change without disrupting the market system itself.

Communist economies collapsed because their artificial system of prices did not speak the "economic truth". There is reason to suppose that world market prices for many commodities do not speak the "ecological truth". Does this signal danger for the market system *per se*? In this context, an important difference between long-term price adjustments for labor and price adjustments for natural resources is that the former could occur within a country and without significant international agreements, while the latter cannot.

Eco-restructuring radical enough to bring the economy into harmony with the environment — i.e. to bring "economic truth and "ecological truth" into coincidence — implies major structural changes. The restructuring has to be international in scope. Economic instruments should be explicitly designed for reaching the goal of long-term sustainability, in sharp contrast to the traditional *ad hoc* approach so often employed for environmental protection during the past twenty years. Among the economic instruments to be considered one might include resource taxes (in exchange for other tolls, for instance income taxes), preferential insurance and liability rates, preferential buying by state authorities, temporal subsidies, R&D support, and others.

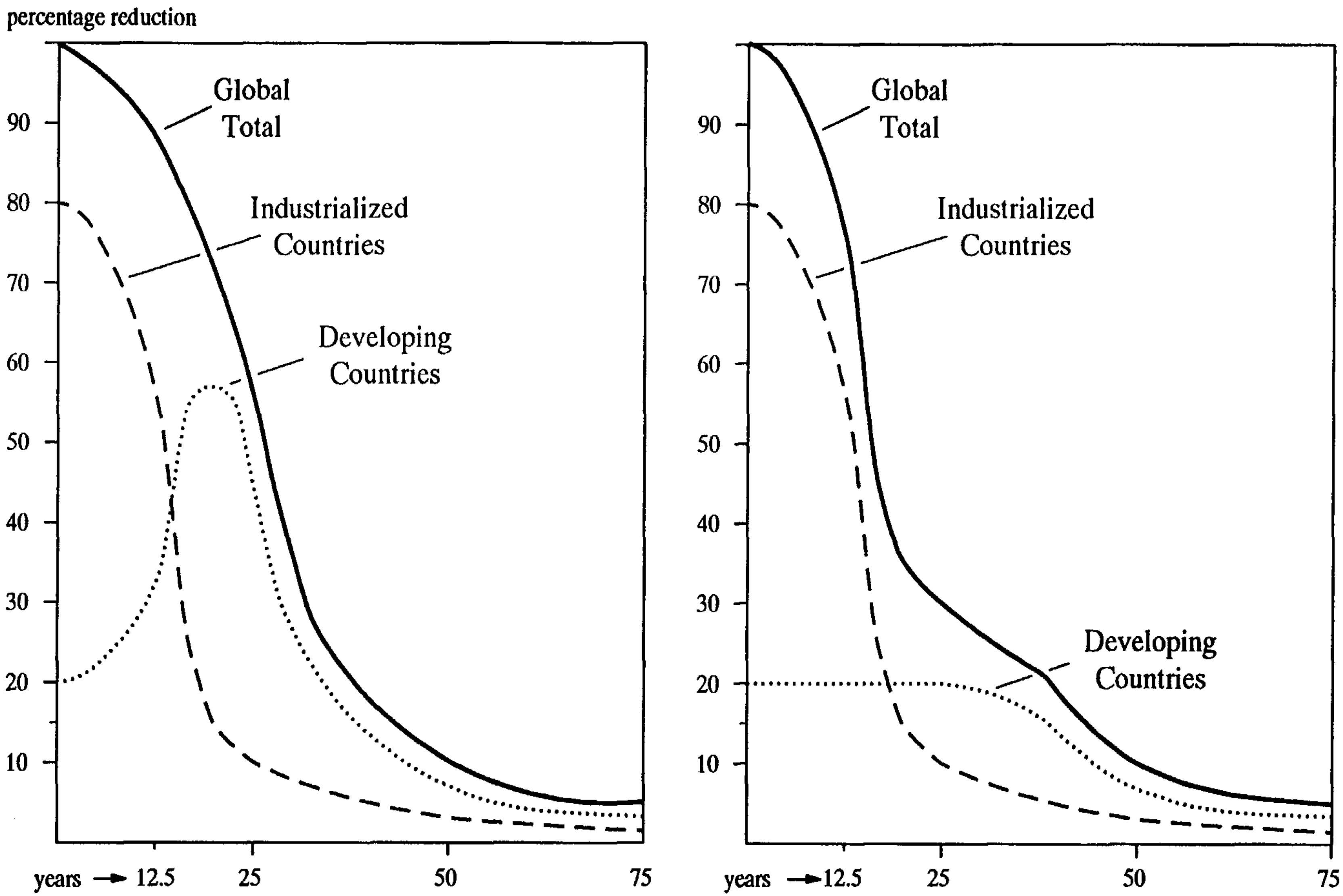
It has become fashionable in recent years to bemoan the population increases in certain parts of the world as being ecologically unsustainable. There can indeed be no doubt that every human being alive today is an "ecological liability"! However, the environmental impact (entropy production) of persons living in certain G-24 countries is roughly 15 times as high as that of people living in some parts of the Third World.

The Ecological Security Factor

A 50% reduction of the global anthropogenic energy/material streams may not be sufficient, but would be a first and major step toward stabilizing the ecosphere. At this time, close to 80% of the global production of commodities (except basic foodstuffs) is used for providing the material welfare of the people in the industrialized world. (Here it is appropriate to include the post–communist countries, the asiatic "Tigers", and some of the oil producing states). These countries account for around 20% of the present world population.

Assuming equitable global economic development leading to a world in which every region has access to roughly the same "goods" on a *per capita* basis, the large majority of people would increase their consumption of energy and materials. In order to make a 50% reduction of global anthropogenic material flows possible (see *Figure 1*), enormous increases in the energy productivity and materials productivity of our economy will be needed. To put it another way, western type goods and services as we know them today would have to be "de-materialized" (or, more accurately, "de-entropized"), on the average, by ***a factor of ten,***

Figure 1: Hypothetical Reduction of Global "Waste" Streams   Source: F.B. Schmidt-Bleek



Hypothetical reduction of global material substances under the assumption that there is no further population increase. In the left hand graph an increase of global material consumption has been assumed for the developing countries whereas in the right hand graph the material intensity for the developing countries was kept constant until it begins to fall off.

more or less. As we have indicated above, this de-materialization refers to a "cradle to grave" analysis for all economic outputs.

Of course, the other obvious alternative would be to cut down the per capita availability of goods and services by a factor of ten or more. This is the alternative many of the environmentalists c. 1972 accepted as inevitable. We argue, below, that a radical dematerialization is both technically and economically feasible, given the political will, and the necessary time (half a century or so).

How Much Can Resource Productivity be Increased?

As rising labor costs in the 19th century increasingly became one of the determining factors for successful economic competition, the important breakthroughs in manufacturing were due to higher efficiency of already existing procedures. Instead, radical improvements were achieved by introducing new procedures, using completely new kinds of tools and machines. These changes achieved vastly superior results, not only in quantity, but later in quality, compared to previous approaches. Between the 1840's and the 1890's labor productivity in U.S. manufacturing increased by well-documented factors of 20 to 100. There were extreme cases of labor productivity increasing by factors of 10000 and more.

As indicated above, there has been little incentive in the past to raise the question: how much material welfare can I squeeze out of one kilowatt, or one liter of water, or one kilogram of iron mineral? The reason is simple: compared to capital and labor, resource costs have been extraordinarily low. This is due to the general failure of prices to reflect the social costs of environmental externalities.

Although a detailed justification cannot be provided in a short paper such as this, we believe that from a technical point of view, it would be feasible to reach an overall ten-fold or even higher de-materialization of present services, on the average, on a cradle to grave basis. Of course this would require even more radical changes in some areas (for instance, communications, entertainment, health care, and packaging), to compensate for lesser improvements in others. Part of the needed increase in factor productivity can be achieved by increasing product life and/or re-use and re-manufacturing. This is mostly a question of institutional (and price) change. A great deal could be achieved, for instance, by converting waste plastics into wood-substitutes for building purposes.

The most difficult challenge, without doubt, is the combination of housing and transportation sectors. Dispersed, low density housing patterns, exemplified by the U.S., cannot be effectively served by energy-efficient public mass transportation means. Many city and town planners have addressed the linkage between housing patterns and transport needs by designing utopian communities in which private automobiles play little or no role. So far, such efforts have met with little acceptance. Whether this would change in a world where energy and materials become far more expensive, relative to labor and capital, than they are today, remains to be seen. However, as we said above, from a technical point of view, we think the problems are soluble, without sacrificing amenity values.

Clearly, any such radical change (in the face of resistance from a host of established institutions and interest groups) would require tremendous and well focused innovation and development effort, public and private alike. Of course it would also mean that "service delivery" systems might, at the end of the day, look and function quite differently from current gadgets and systems. And it would likely also mean a further shift toward the service sector, because the retaining of materials in circulation within the technosphere through long term maintenance and repair would likely increase in importance.

In general terms, the employment market would be affected positively by a price shift that increased energy/materials costs, relative to labor. Putting it another way, labor costs would have to drop, relative to other factors of production. This would mean more jobs. Detailed impacts on particular sectors or professions are much harder to predict, of course, but nothing points to a decrease in employment opportunities.

Major technical changes take 10 to 20 years just to gain some momentum, and much longer to diffuse widely throughout society. A radical de-materialization should be expected to take at least half a century to accomplish, as the substitutions of coal for wood, petroleum for coal, and electricity for gas light, each required about half a century. But as recent history has shown, during a 40 to 60 year period the technical underpinnings of industrial societies can change so radically, that a 10 fold increase in energy/materials productivity may occur almost painlessly in many countries, if the public policy and economic signals point in the right direction.

The Design of "Dematerialized" Services

The radical dematerialization contemplated above will rarely, if ever, be accomplished by attempting to "ecologize" current products. This is because our currently popular products were created, optimized, and utilized under economic conditions that do not reflect ecological constraints. To create the "de-materialized" products, systems, and services of the future, the first step will have to be to clearly define the "bundle of services" that are desired or needed (sufficiency aspects may enter the picture here). Subsequently the most de–materialized and least toxic solution must be designed.

In addition, other critical attributes must be considered: longevity, reliability, serviceability, transportation, packaging, and ultimate disposal. The latter issue involves issues pertaining to reparability, re-manufacturing (mechanical and chemical), and re-use. In addition, more traditional quality features (safety, health, etc.) must also be considered.

The fact that considerable de-materialization seems feasible from a technical point of view does not, however, imply that it will happen. As we have indicated repeatedly, the price and other economic or legal signals are not sufficiently encouraging at this time for the private sector to move in this direction. Deliberate adjustment measures by governments would therefore be a precondition. As was the case when social legislation "corrected" the terms of trade in the labor market, beginning some 120 ago, new long-term social contracts, as well as new institutional arrangements, to prevent mankind from leaving this planet in an uninhabitable condition for future generations. National governments should take the first steps, particularly those of economically strong countries. But ultimately, only international agreements can secure the success of bringing economies into harmony with nature.

For the energy sector, E.U. von Weizsäcker has recently described a scenario how first steps may be accomplished under socially and politically acceptable conditions [v. Weizsäcker 1991]. Social adjustments normally take a human generation or more. Taking technical development restrictions into consideration, eco-restructuring plans must be subtle and long term, if they are to be realistic. Because the ecosphere is the source and the sink for man-moved materials of all people, international harmonization is needed more than ever before to move toward a global sustainable development.

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