RESOURCES, SCARCITY, GROWTH AND THE ENVIRONMENT

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Thermodynamics and natural resources

The term `resources' is used in many ways in different disciplines. For purposes of this paper, a resource is an essential input to the economic process. Resources may be material or immaterial (e.g. information) and material resources may be of natural origin or man-made. Services provided by nature (e.g. `assimilative capacity') are also sometimes called resources. However, in this paper, the term natural resources is restricted hereafter to energy – actually exergy– carriers and raw materials extracted from the natural environment by intentional human activity.

The word *energy* is widely misused, and for the sake of precision I will introduce a different term, *exergy* that is less familiar but more precise. Energy is a conserved quantity (the first law of thermodynamics) , which means that it can only change form or quality (e.g. temperature) but can never be created or destroyed.. Energy and mass are equivalent (E = mc2) and inter-convertible in principle. (Nuclear reactions convert infinitesimal amounts of mass into energy, for instance.) But when a non-nuclear fuel burns, both the mass and the energy-content of the fuel (and air) are exactly the same as the mass and energy-content of the waste products. What has changed is the *availability* of the energy in the fuel for doing work. This availability is quantifiable. A number of terms have been used for it, including `available work', `availability', and `essergy', but by general agreement (in Europe at least) it is now denoted `*exergy*.'

The formal definition of exergy is the maximum amount of work that can be extracted from a material by reversible processes as it approaches thermodynamic equilibrium with its surroundings. Exergy is therefore a quantity that is not definable in absolute terms. It can only be defined in terms of a reference state, namely the environment. But exergy can be calculated for any material with reference to whatever environmental medium that material would be likely to reach thermodynamic equilibrium with, namely the atmosphere, the ocean or the surface layer of the earth's crust (topsoil or subsoil). Thus gases tend to equilibrate with the atmosphere, liquids or soluble solids with the oceans, insoluble solids with the land. (Detailed tabulations can be found for many materials in Szargut *et al* [1988] and some additional ones are in Ayres and Ayres [1999]). The exergy content of most fuels, per unit mass, is very nearly the same as their so-called enthalpy (heat) content per unit mass. However, even minerals and metal ores have characteristic exergy values, which are really measures of their `distance' from thermodynamic equilibrium as defined by the average mix of materials in the lithosphere. The higher the grade of ore, for instance, the more it is unlike – hence *distinguishable from* – the surrounding rock and the greater its exergy value.

The above paragraph has two points of relevance to larger environmental considerations. First, of all, for any given metal or other chemical element it can be seen that the greater the exergy content of the ore per unit of mass (i.e. the higher its grade, or distinguishability from its lithospheric environment), the less exergy is likely to be required to concentrate it and refine it. (All other factors remaining equal, of course.) In short, exergy is a very general way of keeping track of physical scarcity, on the one hand, and difficulty of separation and purification, on the other. Obviously this is not to say that the exergy required to extract chlorine from rock salt is in any way comparable to the exergy required to refine copper or extract gold from placer deposits. However, it is clear that different copper ores, or gold ores, and especially, ores with different compositions (in terms of sulfur and other more or less valuable by-products) can be meaningfully compared in exergy terms. It seems reasonable to postulate that two ore bodies of equal size and equally distant from markets and confronting similar labor and capital costs, will probably have monetary values – taking into account both beneficiation, smelting and refining costs and by-product credits – pretty much in proportion to their respective exergy values.

This leads to a second point of relevance, namely the possibility of measuring all kinds of resource reserves in common (i.e. exergy) terms, for purposes of both international and temporal comparison [Wall 1977, 1986]. As already noted, it is possible to measure copper reserves, iron ore reserves, coal reserves, petroleum or gas reserves and forest biomass in the same units (e.g. kJ or pJ). To be sure, these different resources do not have equal market values per unit mass. Nor do they have the same market values per unit exergy content. Market value of finished materials is *not* proportional to their direct or indirect exergy content. This is partly because some resources – natural gas, for instance – can be used with an absolute minimum of treatment (mainly to remove hydrogen sulfide) whereas others, such as copper ore, require a great deal of treatment indeed to yield a useful product. This treatment consumes huge amounts of exergy from fuels, not to mention other intermediates (like solvents) and capital equipment. Equally important, some materials, such as platinum, palladium and rhenium, have enormous economic value because of their unique physical properties (e.g. as catalysts). Yet other elements have very little economic value because they have no specially useful properties or because they are extraordinarily difficult to work with. For instance, the light metals, beryllium, lithium and magnesium are quite commonplace in the earth's crust, but rarely used in industry, at least in relation to their availability in the earth's crust. The 9th most common metal in the earth's crust, rubidium, has virtually no industrial uses.

A third point might be mentioned here, though it is unrelated to scarcity. It is that, just as resources can be measured in common physical (exergy) units, so can pollutants [Ayres et al 1998; Ayres and Ayres 1999 p. 48]. The exergy content of wastes is not necessarily proportional to the potential environmental harm the wastes may cause, but the exergy content of a waste stream is a rough measure of its reactivity in air or water, i.e. its tendency to initiate uncontrolled chemical reactions in environmental media. In this regard, one can say that, although the exergy content of a waste stream is not a measure of human or eco-toxicity, it is certainly a better measure of its potential for causing harm, than is its total mass. The simple implication is that exergy embodied in wastes per unit service (XEWPS) would be a far better indicator than the better-known scheme known as mass input per unit service (MIPS), even though it is clear that neither MIPS nor XEWPS can capture subtle effects such as ecotoxicity or carcinogenicity.

The above remarks have direct relevance to the notion of using indirect mass flows associated with mining, agriculture and construction as a `measure' of sustainability by the Wuppertal Institute [Schmidt-Bleek 1992, 1994; Bringezu 1993; Adriaanse et al 1997]. These indirect mass flows are very large compared to the mass flows of economically important processed materials, such as fuels, chemicals and metals. This fact has impressed many people. However, the environmental damage caused by indirect flows such as the removal of mining overburden or excavation for road building are strictly local and comparatively minor in relation to the magnitudes of the mass-flows involved. Would anybody seriously equate the damage potential of a ton of chlorine or chlorinated hydrocarbons with a ton of subsoil? This point is immediately obvious from an exergy perspective: subsoil or overburden are essentially indistinguishable from the surrounding soil or rock, whence the exergy embodied in these inert mass-flows (on average) is essentially zero *by definition.*[1]

Dematerialization

A popular environmental slogan these days is `dematerialization'. It follows almost automatically from the notion that large mass flows are environmentally harmful, whence it seems that less harm must follow from reduced mass flow. This is another potentially misleading proposition.

Many examples have been presented to demonstrate the supposed trend towards dematerialization in industrial societies. The primary example, of course, is the computer chip. Undoubtedly the size and weight of computer chips, and products containing them, from radios and portable telephones to computers, are much less massive – and use less electric power – than their less powerful counterparts ten, twenty or thirty years ago. To a lesser extent, the same trend can be observed in a variety of other products.

On the other hand, there are two countervailing trends that are often forgotten. One is the so-called `rebound effect'. To the extent that dematerialization is accompanied by lower costs and real savings to consumers, demand for the products tends to increase. In the case of `mature' products approaching demand saturation, the savings to consumers may be spent on other goods and services, which may or may not be less materials/exergy intensive. However for products that are still rapidly evolving and for which markets are growing, the lower cost of a unit may simply encourage the consumer to buy more of them or to replace them sooner than he/she would otherwise do. This has almost certainly happened in the case of personal computers, digital assistants, cellular phones and so on. It is by no means clear that the total mass of consumer electronic products sold each year is declining.

Apart from the rebound phenomenon, there is another trend that may be working in the opposite direction. Simply stated, as computer chips become smaller and more compact the manufacturing process becomes more and more complex. The ratio of indirect material consumption to material actually embodied in the product is extremely large. A chip weighing 1 gram requires processing in which several hundreds or even thousands of grams of photo resists, acids, solvents and neutralizers are used and discarded. Virtually none of the materials involved are recovered for recycling.

This situation is in marked contrast with conventional metal or plastic products. Stone, glass, clay and concrete products generate very little waste during the quarrying, mining and processing of the materials, and even less is lost during construction. Forest products are also used quite efficiently: wood that is not used directly as lumber is generally converted into fiberboard or paper. Even the wastes are burned as fuel. In the case of paper, most of the waste is at the consumption end. Only in the case of metals is the waste mass during mining, concentration and smelting significantly greater than the mass of the refined product. (This is especially true for copper and even more so for the precious metals.) However, from that point on in the manufacturing process, losses are small and mostly recovered. Again, it is mainly in the final consumption stage that significant unrecoverable losses do occur.

In short, the micro-electronic products that are commonly cited as examples of dematerialization are really illustrations of quite a different and less favorable trend.

The problem of scarcity in economics

Until the last few hundred years, land was virtually the only economic `resource', with a few minor exceptions, mainly metals. However the most productive agricultural land in Europe and Asia was already occupied and fully utilized by the end of the 18th century. The idea of resource (land) as a factor of production originated with the French physiocrats, especially Quesnay, and Adam Smith [Kuczynski 1971; Smith 1763(1978), 1776(1976)]. Quesnay and Smith were disputing Locke's assertion [Locke 1698(1960)] that land only generates wealth through the application of labor and tools. He regarded tools as a `store' of labor. Obviously Locke's view was the intellectual precursor of the so-called labor theory of value, as refined by Marx and others [Weissmahr 2000].

The notion of scarcity as a constraint on economic growth goes back to Malthus [Malthus 1798(1946)]. It was only later that other natural resources, and especially exhaustible resources, began to be seen as `factors of production' in their own right.

There have been number of cases of actual resource scarcity – or even exhaustion – usually limited to a particular resource or country. To name a few historical examples: charcoal became scarce in western Europe, especially England, by the 17th century. (Due to land clearing for agriculture and grazing, and ship-building.) Coal came into general use in Britain as a substitute for charcoal in the 18th century. Sperm whales, the preferred source of lamp oil and tallow for candles became scarce in the mid-19th century. Whaling ships in those days were often away for as long as three years; this prompted a search for substitutes. Kerosine, derived from `rock oil' (petroleum) was the eventual choice. (Gasoline was a low-value by-product until about 1910).

Natural fertilizers – guano and nitrate deposits from the West coast of South America – were also largely exhausted by the end of the 19th century. However superphosphate from bones, and later from mineral apatites, replaced natural guano. Similarly, synthetic nitrogen-based fertilizers from coke-oven gas, calcium cyanamid and finally synthetic ammonia provided alternative sources of agricultural nutrients. Natural rubber appeared to be a problem at the outset of World War II, thanks to the Japanese conquest of Indochina and Malaysia, the major loci of rubber plantations; however synthetic rubbers from petrochemicals soon became available to replace the natural rubber. Natural sulfur deposits have largely been exhausted, but sulfur is now obtained easily from natural gas and from smelting copper, lead and zinc. Natural cryolite, a sodium-aluminum fluoride mineral which is needed for aluminum smelting by the electrolytic process, has long been exhausted. Now cryolite is manufactured synthetically. Up to now, scarcities have not proven to be obstacles to economic growth; more often they have been stimulants to innovation.

However, some resources are required in such massive quantities that substitutes are out of the question. Fresh water and topsoil – necessary for agriculture – are two obvious examples. It is true that plants can be grown in greenhouses. This technique may be applicable to a few high-value products like flowers. But it is inconceivable that such special techniques could ever be a large-scale substitute for normal agriculture. It is also true that fresh water can be obtained from salt water, by desalination. But even if much better techniques of desalination are developed, the desalination process will always by very energy-intensive. Available energy (exergy) is, increasingly, the key to finding substitutes for other scarce resources. As Alvin Weinberg has said, energy – he meant exergy – is “the ultimate resource” [Weinberg 1978].

The industrial economy is currently dependent on fossil fuels. Hydro-power is still under-utilized in some parts of the world, but the potential for further utilization through large-scale projects such as the `Three Gorges’ dam on the upper Yangtze River in China is limited and, to say the very least, controversial. Nuclear power appeared at one time to be the long-term answer. But the dangers and costs were significantly underestimated from the start, and the public is increasingly suspicious of the claims of its proponents. There is no longer any reason for confidence that nuclear power will replace fossil fuels to any significant extent during the coming decades. The contrary is more likely.

The availability of fossil fuels has been a subject of controversy for a long time. There have been a number of `scares’ since 1865 when W. S. Jevons predicted that the British coal reserves would be exhausted within a few decades [Jevons 1865]. A similar concern arose with respect to petroleum reserves in the 1920s, then again in the aftermath of World War II, when the so-called Paley Commission (among others) took up the question in the US.[2] The scarcity issue was revived once again in the early 1970s, even before the oil embargo precipitated by the Sinai War between Israel and the Arabs.[3] However, up to now none of these scares has been well-founded. Consequently, there is a tendency in mainstream economic circles, to deride `neo-Malthusians' and to assume that resource scarcity will never be a problem, because new sources or substitutes will always be forthcoming [e.g. Simon 1980; Kahn and Simon 1984; Simon et al 1995].

Exergy and economic growth

The application of thermodynamics to economics has a surprisingly long history. From a biological-ecological perspective, solar exergy is the ultimate source of all life on earth, and therefore "the wellspring of economic value". This view was first proposed by the Nobel laureate chemist Frederick Soddy [1922, 1933], but was ignored or dismissed by economists. (Soddy's contribution was reviewed a few years ago by Herman Daly [1980]). The energy theory of value was openly revived by the ecologist Howard Odum [1971, 1973, 1977], while economist Nicolas Georgescu-Roegen took a slightly different route, essentially treating `low entropy' as a scarce resource to which prices should presumably be attached [Georgescu-Roegen 1971, 1976]. However Georgescu-Roegen's theories remained essentially abstract. A number of attempts to justify this view of the economy by energy analysis and econometric methods using empirical data followed, viz. [Hannon 1973, 1975; Herendeen 1974; Costanza 1980, 1982; Hannon and Joyce 1981; Cleveland et al 1984].

However, despite the impressively close correlations between gross exergy consumption and macro-economic activity revealed by the work of the so-called `biophysical' group cited above, the underlying energy (exergy) theory of value is difficult if not impossible to justify at the micro-economic level. In any case it is quite at odds with the paradigm of mainstream economics which is built on a value theory based on human preferences [e.g. Debreu 1959]. Nevertheless, exergy analysis has its uses. Exergy is a general measure applicable to all material resources at any stage of processing, including minerals and pollutants. As noted previously, it can be applied to the evaluation and comparison of resource availability [e.g. Wall 1986]. From a theoretical perspective, the economic system can be viewed as a system of exergy flows, subject to constraints (including the laws of thermodynamics, but also others) and the objective of economic activity can be interpreted as a constrained value maximization problem (or its dual, an exergy minimization problem) with value otherwise defined [Eriksson 1984]. Exergy analysis can also be used empirically as a measure of sustainability, to evaluate and compare wastes and emissions from period to period or country to country [Ayres *et al* 1998].

Apart from other problems, the biophysical approach offers no real explanation of why exergy consumption (or production) drives growth. The close correlation is evident, but even a high degree of correlation does not necessarily imply causation. In other words, the fact that economic growth tends to be very closely correlated with (commercial) exergy consumption – a fact that has been clearly demonstrated – does not *a priori* mean that energy consumption is the cause of that growth. Indeed, most economic models assume the opposite: that economic growth is responsible for increasing energy consumption. This automatically guarantees the correlation. It is also conceivable that both consumption and growth are simultaneously caused by some third factor. The direction of causality must evidently be determined empirically by other means.[4] I argue, primarily from first principles, that the causality in this case is not uni-directional, but bi-directional (i.e. mutual).

In brief, there is a generic feedback cycle that works as follows: cheaper energy and power (due to discoveries, economies of scale and technical progress in energy conversion) enable goods and services to be produced and delivered at lower cost. This is another way of saying that exergy flows are `productive'. Lower cost, in competitive markets, translates into lower prices which – thanks to price elasticity – encourages higher demand. Since demand for final goods and services necessarily corresponds to the sum of factor payments, most of which flow back to labor as wages and salaries, it follows that wages of labor and returns to capital tend to increase as output rises.[5] This, in turn, stimulates the further substitution of fossil energy and mechanical lower for human (and animal) labor, resulting in further increases in scale and still lower costs. The general version of this feedback cycle is shown schematically in *Figure 1*.

Based on both qualitative and quantitative evidence, the positive feedback relationships sketched above imply that physical resource flows have been, and still remain, a major factor of production. It is not surprising, therefore, that including a resource flow proxy in the neoclassical production function (as the biophysical group has done), without any exogenous time-dependent term, seems to account for economic growth quite accurately for significant time periods, as noted above.

As indicated earlier, among many neoclassical economists, strong doubts remain. It appears that there are two reasons. One is the causality argument already sketched above. The other reason is theoretical: national accounts are set up to reflect payments to labor (wages, salaries) and capital owners (rents, royalties, interest, dividends). In fact, GDP is the sum of all such payments to individuals. If labor and capital are the only two factors, neoclassical theory implies that the productivity of a factor of production must be proportional to the share of that factor in the national income. This proposition gives the national accounts a fundamental role in production theory, which is intuitively attractive.

As it happens, labor gets the lion’s share of payments in the national accounts, around 70 percent, and capital (i.e. interest, dividends, rents, and royalties) gets all of the rest. The figures vary slightly from year to year, but they have been relatively stable (in the US) for most of the past century. Land rents are negligible. Payments for fossil fuels (even in `finished’ form, including electric power) altogether amount to only a few percent of the total GDP. It seems to follow, according to the received theory of income allocation, that energy and natural resources are not a significant factor of production and can be safely ignored.

Of course, there is an immediate objection to this line of reasoning. Suppose there exists an unpaid factor, such as environmental services? Since there are no economic agents (i.e. persons or firms) who receive money income in exchange for environmental services, there are no payments for such services in the national accounts. Absent such payments, it would seem to follow from the above logic that environmental services are not economically productive. This implication is obviously unreasonable. In fact, it is absurd.

The importance of environmental services to the production of economic goods and services is difficult to quantify in monetary terms, but conceptually that is a separate issue. Even if such services could be valued very accurately, they still do not appear directly in the national accounts and the hypothetical producers of economic goods would not have to pay for them, as such.[6] There are some payments in the form of government expenditures for environmental protection, and private contributions to environmental organizations, but these payments are counted as returns to labor. Moreover, given the deteriorating state of the environment, it seems clear that the existing level of such payments is considerably too low. By the same token, the destruction of unreplaced environmental capital should be reflected as a deduction from total capital stock for much the same reasons as investment in reproducible capital are regarded as additions to capital stock.

Quite apart from the question of under-pricing, the apparent inconsistency between very small factor payments directly attributable to physical resources – especially energy – and very high correlation between energy inputs and aggregate economic outputs, can be traced to an often forgotten simplification in the traditional theory of income allocation. In reality, the economy produces final products from a chain of intermediates, not directly from raw materials or, still less, from abstract labor and abstract capital.

Correcting for the omission of intermediates by introducing even a two-sector or three-sector production process, changes the picture completely. In effect, downstream value-added stages act as productivity multipliers. Or, to put it another way, the primary sector can be considered as an independent economy, producing value from inputs of physical resources and small inputs of labor and capital. The secondary sector (or economy) imports *processed* materials from the first sector and uses more labor and capital (and processed materials) to produce still higher value products, and so forth. Value is added to materials step by step to the end of the chain. This enables a factor receiving a very small share of the national income, or even none at all, to contribute a much larger effective share of the value of aggregate final production. By the same token, this factor can be much more productive than its share of overall labor and capital would seem to imply [Ayres 1999].

I believe that another major part of the future research agenda should be to clarify the role of natural resource flows as drivers of economic growth. The idea that growth can continue in the future without concomitant increases in resource consumption is something that economic theorists are comfortable with, because resources play no role in standard growth theory. However, the idea of reducing resource consumption by regulation or by taxation to increase costs to users, is very frightening to manufacturers and all kinds of businesses. Can economic growth continue if resource consumption decreases? If so, how can such a result be achieved? This is probably the most serious question that economic policy-makers will have to deal with in the coming years.

Scarcity vs abundance: the geological perspective

Geologists classify elements as geochemically abundant and geochemically scarce. The first group consists of 12 elements, of which 4 are widely used metals (aluminum, iron, magnesium and manganese) that accounts for 99.23% of the mass of the earth's continental crust. Silicon, calcium, sodium, potassium, titanium and phosphorus are also in the top 12, though rarely used in metallic form. Only iron, among them, has an atomic weight greater than 40. The other 90 or so known elements, including all other metals, altogether account for just 0.77% of the crustal mass. (A number of the transuranic elements, including plutonium, are not found in nature at all, but can only be synthesized in high energy physics laboratories.) The point is that all common rocks are composed of compounds of one or several of the abundant light elements. Hence it has appeared safe to assume [e.g. McKelvey

1960] that there is a standard (quasi-Gaussian) grade-abundance distribution, such that larger quantities of every element will be available at progressively lower grades, down to the crustal average.

For the geochemically scarce elements there are surprisingly different distributional patterns. Beryllium is an interesting example. It is not one of the scarcest elements, but although it is a component of something like 40 minerals, and 50 other minerals containing beryllium are known, yet only one (beryl) is found in (a very few) mineable deposits. Rubidium is another peculiar case: it is not a primary constituent of any known mineral. Yet rubidium is the 9th most common metal and constitutes close to 0.31% of crustal mass.

On the other hand, scarcer elements are found in sizeable deposits at concentrations thousands of times greater than the crustal average. Examples include chromium (0.2% of crustal mass); zinc (0.132% of crustal mass); nickel (0.08%), copper (0.055%), tin (0.040%) and lead (0.016%). These metals, especially copper, are all mined in large tonnages.

The peculiarities of distribution are consequences of the earth's structure and the chemical characteristics of the elements. In the first place, heavier elements are naturally more concentrated in the core near the center of the earth, where they remain in a solid state under very high pressure. The solid (nickel-iron) core is surrounded by a semi-liquid mantle, on top of which floats a lighter solid crust made up of the lighter elements and their compounds. The geological system resembles a blast furnace in which molten metals fall to the bottom and the lighter slag floats on top.

The presence of heavy metals in the crust (analogous to slag), as distinguishable minerals – rather than atomic substitutes – usually reflects a magmatic intrusion from the molten mantle, resulting from some tectonic or volcanic disturbance. Mineral deposits are formed following such intrusions by differential cooling and crystallization, dissolution in super-heated brines which later penetrate and crystalize in cracks in the rock, and by chemical reactions with the crustal rock [Bachmann 1960; Kesler 1994]. Other mechanisms for mineral formation and segregation on the earth's surface include differential weathering, differential deposition of weathered minerals, reactions with atmospheric gases, and biological activity. But the opportunities for scarce heavy elements to mineralize near the crustal surface are themselves very scarce.

Only the naturally enriched minerals in the crust can be concentrated by conventional physical-chemical means. Mineral compounds of the scarcest elements do not exist, as such, in common crustal rocks such as granite or feldspar. Atoms of the very scarce elements are almost entirely distributed as *atomic substitutes* in minerals –mainly oxides – of the more abundant light elements. These substitutions are not entirely random, of course, because they depend to some extent on the crystal structure of the `parent' rock and the size and shape of the gaps that occur therein. For instance, lead is mostly an atomic substitute for potassium, while zinc is mainly an atomic substitute for magnesium. Extraction of metals that are present only as atomic substitutes in other minerals is feasible only in a few cases, mainly where they are contaminants that must be removed for other reasons. For example, antimony, arsenic, bismuth, cadmium, selenium, silver, tellurium and gold are all associated with lead, zinc and copper ores. Once the `parent' minerals have been concentrated and smelted, it is feasible to separate and extract the other minor contaminants from slags or `slimes' in secondary processes.

Taking the foregoing facts into consideration, it seems likely (though as yet unproven) that certain geochemically scarce elements tend to have a bimodal distribution (*Figure 2*), in which the smaller peak – corresponding to relatively high concentrations – reflects geochemical mineralization, while the main peak reflects atomic substitution in more common minerals, mainly silicates [Skinner 1976a,b].[7] The implication is that certain metals – including some of the ones that have been industrially important for a very long time – may be effectively exhausted (for practical purposes) within a few decades [COMRATE 1975].

Copper and lead illustrate the problem. Copper from currently mined ores averages around 0.8% in grade globally (0.5% in the U.S.), while 50-100 gigajoules (gJ) are required to produce a ton of pure metal from the ore, depending on the grade of ore and the age of the facilities. The exergy required for mining and concentration (to about 25% Cu) depends strongly on the grade of ore; current figures range from 11-15 GJ/t for underground mines and from 22.6-35.5 GJ/t for open pit mines [Landner and Lindestroem 1999 Table 4.4 p.59]. Technological progress may reduce this figure still further, over time, but not by more than a factor of two or three. Meanwhile the ore grade will continue to decline, with opposite consequences *ceteris paribus*. The most advanced smelting and refining facilities today require as little as 10 GJ/t to convert concentrate to pure metal, and this figure is expected to drop soon to 7.3 GJ/t in one Swedish facility [op cit pp. 60-61]. However the relatively low energy requirement for smelting nowadays arises from efficient exploitation of the heat energy released by the exothermic reaction between atmospheric oxygen and sulfide ores.

However, copper present as atomic substitutions in common crustal rocks has a grade of around 90 ppm (0.009%) for basalt, 70 ppm for black shale, 50 ppm for shale, and 15 ppm for granite and sandstone. The average is 60 ppm. Separating the copper atoms from the surrounding silicate matrix would require vastly more energy (exergy) than current processes. In other words, to mine the earth's crustal rock for copper, after the reserves of mineralized copper are exhausted, would increase energy requirements per ton by a factor of hundreds or even thousands [Skinner 1976]. This is called the `mineralogical barrier' (*Figure 3*).

The case of lead is even more dramatic. Lead sulfide ores with a grade of 2% (and as high as 7%) are being mined now, and barely 10 gJ is needed to produce a ton of the pure metal from ore. However to obtain lead from atomic substitutions in crustal rock, where it has a grade of around 20 ppm (0.002%) would require something like 400,000 gJ per ton, or 40 thousand times more than the current energy cost of lead. Even the most optimistic assessment of future energy availability would necessarily exclude common rocks (or ocean water) as potential resources of these metals.

A similar situation may well apply to hydrocarbon resources, especially petroleum. There is an interesting background story. In 1956, based on prior work on mineral ore depletion in Europe by D. F. Hewett (1929), geologist M. K. Hubbert predicted that US petroleum production would peak between 10 and 15 years after the date of the prediction [Hubbert 1956]. This prediction was made on the basis of a variety of data, including the fact that the rate of discovery of oil in the US (not including Alaska) had peaked in 1940 and declined sharply thereafter. In 1962 he refined his predictions, using additional data on discovery rates, reserves and production. He found that the rate of crude oil discoveries (including Alaska) had already peaked (in 1957), and that proved reserves were then at their peak (1962). Using a quantified version of Hewett's scheme, he predicted that peak production in the U.S. would occur in 1969. This proved to be accurate (the actual peak was 1970.) The Hubbert predictions were so disturbing to the oil industry that his methodology was very thoroughly criticized, in hopes of finding a flaw (e.g.[Menard 1981]). However, no serious flaw in the logic was found, or ever has been.

Application of the Hubbert methodology to the global scene is relatively straightforward, except that the data are less reliable. However, the date of peak production is a function of the quantity of recoverable oil, which can remain as a variable.[8] Hubbert himself estimated, on the basis of data available in the late 1960s, that the upper limit of the quantity of recoverable oil in the world (including oil already produced) was between 1350 and 2100 billion barrels of oil (BBO). In that case global peak output would have occurred shortly before the year 2000 [Hubbert 1969].As it happens, his upper limit was a bit too pessimistic. A later study by the US Geological Survey (USGS), using another methodology (based on the distribution of known deposits in terms of specific gravity) concluded that cumulative world production to 1983 was 445 BBO, with demonstrated reserves of 723 BBO and a 90 percent probability that undiscovered reserves would lie between 321 and 1417 BBO, with a most likely value of 550 BBO [Masters et al 1983]. That would correspond to a total ultimately recoverable quantity of 1718 BBO, well within Hubbert's earlier range.

As of late 1997 demonstrated world oil reserves were estimated at 1000 BBO, with another 550 BBO expected to be discovered (most likely value). Total cumulative global consumption had already reached 800 BBO, for an ultimate total of 2350 BBO [Hatfield 1997]. On this basis, the halfway point could be reached in the first decade of the present century, or early in the second decade, depending on political and economic factors. The most recent USGS assessment of world undiscovered oil actually raises the previous estimates by 20% [USGS 2000], citing two new promising regions for exploration, the Greenland shelf and offshore Suriname. (No oil has yet been produced from either region, however).

However, there are also strong reasons to believe that the above is over-optimistic. First among them is that in the two years 1988-89 four Persian Gulf countries and Venezuela increased their demonstrated reserve estimates by a total of 277 BBO, without reporting any discoveries of new oil fields. This could be justified on the basis of revised estimates of recoverability, perhaps, but the chances are good that this reported increase was largely jockeying for influence within OPEC and for purposes of discouraging investment in alternative sources of energy [Campbell 1991]. Another reason for skepticism is that production in the USSR, then the world's second largest producer, peaked in 1988. Several other countries are now approaching peak production. In consequence, the Middle East's share of total world output is necessarily increasing because no other region has the capability of increasing its oil output rate significantly.

A third reason for believing that potential oil discoveries may have been overestimated for political or other reasons is that the global oil discovery rate has declined since the early 1960s, despite periods of high prices and intensive exploration. The optimism of a few years ago about the possibility of very large new`supergiant' deposits under the Caspian Sea, or in Kazakhstan, has not yet been justified on the ground. More to the point, oil prices declined in the 1980s and early 90s because high prices at the beginning of the period stimulated investment in energy conservation (especially in Japan) and simultaneously stimulated exploration. Production capacity increased throughout the 1980s to around 125% of consumption by 1990 [Hatfield 1997]. So prices declined. Then came the Iraqi attack on Kuwait, with the result that Iraq's 3 million bbl/day was subtracted from output, but slow growth in Japan and the US kept demand from exploding. Then the

US recovery after 1992 and rapid economic growth in Asia, especially China, drove demand up sharply. Prices rose until the economic crisis in Southeast Asia (1996-97), cut back demand again. The current (2000) supply crunch was primarily the result of rapid economic recovery in Asia, combined with continued growth in the US and cyclic recovery in Europe. Details apart, the crunch was predicted [*ibid*].

The `age of oil' is not yet ended. Optimists will be cheered by the latest USGS assessment of undiscovered world oil reserves, mentioned above, but several independent lines of argument suggest nevertheless that global peak production will occur near or soon after 2010 [Campbell and Laherrere 1997]. Prices, on the other hand, are likely to continue to be unstable, but the long term trend will be up rather than down. Of course rising prices would eventually bring new sources into production, such as Greenland Shelf oil, Venezuelan heavy oil, Athabaska tar sands and Green River oil shale. The latter sources are potentially many times larger than the global stock of liquid petroleum. On the other hand they will be very much more expensive to extract and refine. Extremely large amounts of capital will be required. This creates a potential supply bottleneck, insofar as it may take a number of decades before new sources could reach the output levels of today. (Needless to say, the efficiency of recovery of usable liquid fuels will be significantly lower and the exergy required for extraction and cracking will be much higher.)

Natural gas is the fashionable alternative to liquid petroleum for the middle of the twenty- first century. However, it is interesting to note that the estimates of producible domestic gas that were made by energy companies and the US Geological Survey in the 1960s and 70s have undergone substantial reduction. Gas reserves have declined since the 1970s. In 1972 the USGS estimated exploitable gas resources in the US at 2100 trillion cubic feet. By 1989 this had fallen eightfold to 263 trillion cubic feet. Meanwhile reserves fell from 293 trillion cubic feet in 1968 to 169 trillion feet in 1992, despite intensive exploration. The amount of domestic gas discovered per million feet of exploratory wells has declined for 50 years, despite improved technologies for identifying good places to drill. Production per well has declined from 500,000 cubic feet per day in 1972 to 185,000 cubic feet per day in 1992.

As with oil, the situation in the rest of the world lags several decades behind that in the US. For many years gas was a by-product of petroleum. As recently as 1986 about 5% of global gas produced (38% for the Middle East) was still vented or flared [Barns and Edmonds 1990, *Figures 3.9* and *3.13*]. This was due to lack of local markets or pipelines. However, the unrecovered proportion of the gas has been declining, partly due to increased capacity to transport gas in liquid form and partly due to increased consumption for petrochemical manufacturing (of methanol, MBTE and ammonia) in Saudi Arabia. Projections made in 1990 suggest a current venting/flaring fraction at 3%. Gas wells are now being drilled for gas *per se*, independently of oil exploration. However, the geology is sufficiently similar to that for oil that the largest terrestrial and offshore gas fields have probably been discovered already. Global proven reserves as of 1991 amounted to 4000 trillion cubic feet, while mean estimates of undiscovered gas reserves were 5000 trillion cubic feet. Assuming normal growth in the gas market plus additional growth due to substitution for oil in some applications, this amounts to a century supply at zero growth rate, but only a 46 year supply at a 3% p.a. growth rate. Assuming the more likely pattern of peak output (and consumption) a few decades hence, followed by a gradual decline, the period of substitution of gas for petroleum must be limited to the first few decades of the coming century. After that, alternatives will probably needed, not only for oil but also for natural gas.

As with oil, there are other potential, but expensive, sources of gas, notably gas dissolved under high pressure in very deep brines and `frozen' gas (methane clathrates) on the edges of the continental shelves. However, for both oil and gas the double peak distribution pattern seems to fit the evidence fairly well.

Several points should be emphasized here. First, short and medium term hydrocarbon supply and prices may (and often do) reflect short term political or economic factors, unrelated to long term prospects. The mysterious increases in reserves during 1988-89 by the five OPEC countries illustrate the point. A more recent case in point is the reported Russian decision to maximize gas exports by the national gas company Gazprom (for hard currency) while depending on nuclear power as much as possible for domestic purposes, even to the extent of rehabilitating many old and unsafe nuclear plants of the Chernobyl type (*Time Magazine*, Sept. 18, 2000). This would be a massive change, since only 22% of 1996 Russian gas production was exported beyond the boundaries of the former USSR It would reduce domestic Russian production of carbon dioxide, thus adding to the potential value of carbon emissions permits that Russia will be able to sell in the carbon-trading market (advocated by the US) that may be created by the Kyoto Accord.

Incidentally, this decision will have adverse environmental impacts, not only in terms of likely radiation leaks[9] but also in terms of non-carbon greenhouse gases. Methane is 30-35 times more potent as a greenhouse gas than carbon dioxide. Hence gas leaks in production, transmission and distribution constitute one of the largest sources of methane in the atmosphere. Estimates vary widely. A Swiss study estimates that transmission losses in Europe average 0.02% for a pipeline of 1000 km in length, and that distribution losses average 0.07 % in the high pressure component of the local distribution system (which consists of welded pipe) and

0.9% in the low pressure component (due to the use of mechanical fittings and joints) [Dones et al 1996 p. 34].This would imply overall system losses of somewhat less than 1%, depending how much gas is taken from the low pressure grid (mainly by households.)[10]. This same study cites 1990 estimates of transmission losses in the Russian Federation ranging from 1% to 10%, with an assumed average of 2% [ibid], which is 100 times greater than the corresponding loss rate for Europe. The Russian gas pipelines are old, badly maintained and very leaky.

However there is reason to believe that the 2% figure – an obvious attempt to be `conservative' – is much too low. In fact, the Russian gas monopoly, Gazprom, produced 565 billion cubic meters (bcm) of gas in 1996, of which only 501 bcm were delivered to customers. Apparently 64 bcm (11%) were lost, stolen, or consumed in transit. Just 75 bcm arrived in western Europe, of which 33 bcm went to Germany [*Economist,* Nov. 29, 1997]. Evidently the quantity of Russian gas lost in transit is twice as great as the amount finally consumed in Germany! The quantity of gas consumed by turbo-pumps for pressurization is not specifically broken out, but for the US it is fairly close to 2% of total flow [Ayres and Ayres 1998, p.76]. For Russia that figure might be doubled due to somewhat longer pipeline distances. That would still leave 7% (c. 40 bcm) as the loss by leakage and/or theft. It seems implausible that theft could account for anything like that much gas. Little, if anything, has been invested in the pipeline system since 1996, so it can be assumed that the loss rate is no lower, and probably even higher, than it was in 1996.

In any case, it seems likely that the distribution of hydrocarbons in the earth's crust is multi-modal, with small peaks for gas and liquid petroleum, and larger peaks for coal, heavy oils and shale. On the other hand, the latter two may be part of a single distribution. What seems very clear, however, is that liquid and gaseous hydrocarbons will be exhausted long before solids. The economic implication of this discussion is clear: the underlying assumption by most resource economists, that resources can always be found in larger quantities at lower grades, is simplistic and misleading.

Renewable vs. non-renewable resources

In the case of non-renewable (exhaustible) resources, the notion of scarcity can be defined and quantified in physical terms by specifying a quantity-grade (abundance) relationship. As noted above, for many of the most critical resources the relationship is unlikely to correspond to a single peak distribution function. However, whatever its shape, a quantity-grade relationship must exist and it is the task of geologists to ascertain its characteristic form and parameters. Once the details of the quantity-grade relationship are known, much can be said about the future trend of extraction costs and energy requirements.

In the case of renewable resources, the situation is far more complex. The stock of fish or timber at any given time is only one of the variables, and not necessarily the most important. The rate of extraction *vis a vis* the rate of regrowth or recovery are crucial, and the rate of regrowth is not fixed in time or place. In the case of a fishery, population recovery depends on the age distribution, competition from other species in the same niche, as well as the balance of predators and prey. A once dominant species (like the North Atlantic cod) can be effectively reduced to negligible numbers if over-fishing allows other competing fish (or even non-fish) species move into the same niche. Similarly, in the forest, spontaneous regrowth depends to some extent on the species and the way in which the cutting was done. Young trees grow faster than older ones. Ideally only the bigger mature trees would be harvested, leaving the young trees room to grow faster. On the other hand, clear cutting favors faster growing non-tree species that can deprive the tree seedlings of light and water, thus inhibiting regeneration. Also, clear-cutting exposes the soil to sun and wind, increases soil temperatures and encourages erosion.

There is little doubt that renewable resources can be scarce, in the sense of being potential constraints on economic activity and growth. However most renewable resources are biological in nature, and depend upon inter-species relationships. These relationships are extremely complex and not nearly well-enough understood to formulate comprehensive theories. There is an urgent need for better theories in this area, however, which depend upon more fundamental research and more extensive data collection.

Optimal consumption and optimal environmental stocks and flows

There is a considerable literature in economics, going back to Harold Hotelling (and `Hotelling's rule') concerning the optimal extraction of exhaustible resources [Hotelling 1931]. The basic idea was that the marginal utility of present vs future consumption should always be equal over time. Excessive consumption in the present would reduce the future stock and availability of the resource, thus raising its price too much, whereas excessive conservation in the present would have the opposite effect. More recently this problem has spawned offspring, including the related problem of optimum consumption of a fixed resource stock. For obvious reasons, the latter became known as the `cake eating problem': in a few words, how much cake should each generation eat so as to be `fair' to the next and subsequent generations. The underlying issue is inter-generational equity.

As a practical matter, the value of present vs future consumption is linked by `time preference’, more commonly known today as the `social discount’ rate, which economists regard as an observable and usually equate to the `real’ interest rate. In brief, the value of consumption in the future is discounted by a constant annual percentage, based on the argument that one always has the choice of spending or saving, and therefore if money in the bank grows at the interest rate, the value of resource stocks reserved for future consumption must increase at the same rate or more if saving (rather than consuming) is to be worthwhile.

The cake-eating problem has no solution unless discounting is assumed. Discounting permits the present generation to consume more than the next generation (and so on), although the cake never completely disappears. The other side of the coin is that discounting values future consumption less than current consumption, which implies that after two or three generations of discounting at the rate of interest, there is no significant value left.

There are many complexities in the real world which make Hotelling’s rule hard to test and difficult to apply, even for exhaustible resources. Among them are uncertainty about resource stocks and future discoveries, uncertainty about future interest rates, and uncertainty about future technology [e.g. Dasgupta and Heal 1974, 1979].

There are also deep questions about the applicability of discounting of any kind to valuation of some `priceless’ resources (such as biodiversity or climatic stability) over very long time periods, especially in the presence of irreversibility [e.g. Page 1977]. The latter issue arises in part because the fundamental paradigm of neoclassical economics assumes fungibility, i.e. that everything with a value can be bought and sold in some market in exchange for money. It follows from that assumption that if the environment is excessively degraded in one period it can be `bought back’ again in a later period. However, there are many reasons for doubt whether this is true for some essential environmental resources.

In modern times this question has been reformulated somewhat in the context of sustainability. There are two nearly polar views on the subject. One view, known as `weak sustainability’ – or strong substitutability – is that man-made products and services are satisfactory substitutes (or could be) for virtually all natural capital assets, whether as factors of production or consumption goods/services [Hartwick 1977; Pezzey 1989; Solow 1992; Pearce and Atkinson 1993]. (Solow allows that the Statue of Liberty and the Grand Canyon might be exceptions.) In this view, the only condition for future sustainability is non-decreasing consumption.

The opposite polar view is `strong sustainability’, which asserts that many environmental services are both essential and non-substitutable. In contrast to the implications of weak sustainability, strong sustainability requires that essential and irreplaceable environmental resources, such as biodiversity and climatic stability, be preserved as such. In other words, ever cheaper personal computers and InterNet access may create many jobs but they will not help feed the poor or protect the island nations of the world from rising sea levels.

An early contribution somewhat consistent with this view was [d'Arge and Kogiku 1973], Dasgupta and Heal [op cit] were among the first to recognize the possibility of `essentiality', i.e. that substitutability might have limits, although the essential minimum might be arbitrarily small. More recently the problem has been taken up in the context of valuation, mainly in the literature of ecological economics, e.g. [Costanza and Folke 1997; Costanza *et al* 1997]. The latter paper, published in *Nature,* attempted to place an extremely large monetary value on nature's services, thus indirectly establishing their essentiality and non-substitutability.

A personal remark is necessary here. Although the results of Costanza *et al* cited above were sensational (to say the least), and widely cited, I believe the effort was seriously misguided and more likely to undermine the credibility of ecological economics than to establish a firm intellectual foundation for strong sustainability. (My critique was published in the *Journal of Ecological Economics* under the title "The Value-Price Paradox", Vol. 25, 1998, pp 17-19.)

The important point that was missed by Costanza *et al* (and many others) can be stated concisely, although the relevance may not be immediately obvious. It is that, contrary to the usual picture (as presented in elementary economics textbooks) demand for products does not approach zero asymptotically as supply approaches infinity. On the contrary, in virtually every case, there is a point at which the demand curve crosses zero and becomes negative. This is another way of saying that far from being willing to pay for additional increments of the substance, the consumer is willing to pay to have some of the excess removed. One can have too much of nearly anything (with the possible exception of money) from food to sleep to sensory stimulation. Music can be too soft or too loud. Light can be too dim or too bright. Food can be too salty or too sweet, or not salty or sweet enough. Philosophers since ancient times have praised the `golden mean'.

However, the key point is that it is equally true of environmental resources; the economic valuation exercises in vogue (`willingness-to-pay' or `willingness to accept')normally assume implicitly that the marginal demand for `resources' (from forests to biodiversity to rainfall) is always positive while the marginal demand for `pollutants' is always negative. The reality is more complicated. Rainfall is a simple example: there can be too little (such an area is a desert) or too much (in a floodprone area). Too little bio-diversity is ecologically risky; but not many of us want to live in a jungle along with thousands of species of rodents, insects, worms, fungi and micro-organisms, many of which treat our bodies, our domesticated animals or our food crops as food or habitat – if allowed to do so. For all the nutrients (N, P, K) and many trace metals – including copper, zinc, nickel and selenium – there can be too little but also too much. Too little results in a deficiency disease; too much is toxic. In some cases the gap between the two is surprisingly small. This is even true of atmospheric oxygen; if the current level were to increase the number and intensity of forest fires would multiply non-linearly. Moreover, the rate of formation of free radicals in the body will increase. (Hence the growing interest in `de-oxidants' such as vitamin C or vitamin E.) On the other hand, if the current oxygen level were to decrease, muscular activity is less efficient, and the cardiovascular system (evolved for sea-level) is stressed.[11]

However, situations where there is `too little' or `too much' of a substance in the environment are relatively rare in natural environments. Many of them are recent departures – mainly anthropogenic – from an evolutionary equilibrium. After all, biological organisms – including humans -- have evolved more or less in equilibrium with either the marine or terrestrial environment, over eons. In effect, the average levels of most nutrients and trace metals in soil or water can be regarded as optimal for the organisms normally present there. To be sure, there are elements and compounds in the environment today that are not utilized or generated biologically, and for which there is no optimal level of exposure. These include most of the very heavy metals, (lead, bismuth, mercury, uranium and silver are examples) as well as many halogenated organic compounds. Such substances are frequently toxic or carcinogenic.. For such substances the biological `demand' curve remains negative at all exposure levels. However, for a great many compounds and elements there is a minimum daily requirement as well as a maximum.

So far I have said nothing very startling. However the implication is that for many of the key environmental resources there is an optimum level of supply. Moreover, when the supply is optimal, the marginal value (or shadow price) is *zero*, by definition. The consumer is satisfied; he or she is unwilling to pay either for additional increments, or for the removal of excess. This situation is illustrated graphically by *Figure 4*. The implication is that many environmental resources have a high marginal shadow price only in situations where degradation is severe.

An important part of the future environmental research agenda should be to provide a credible theoretical basis for the valuation of non-priced environmental services and, indirectly, support for strong sustainability.

Policy implications

Much of what I have said above suggests the need for basic research. This is especially evident in several areas. One is the determination of measures or indicators of sustainability. After all, much of environmental policy is necessarily reactive. The world is too complex to predict the detailed environmental consequences of technological changes, or of policy initiatives in other areas. Thus it is important to monitor the state of the environment on a continuous basis, and to develop tools for ascertaining causal relationships.

It is also important to beware of using misleading indicators, just because they are convenient or available. The increasingly popular use of total mass flow as an indicator of potential damage to the environment is an example of a misleading indicator. If taken seriously it might induce policy-makers to adopt restrictions e.g. on the use of heavy materials in structures, while (perhaps unintentionally) encouraging the use of light materials such as plastics. This sort of response would have very adverse safety implications. The use of embodied exergy as an alternative to mass as an indicator would be much less open to such devastating criticisms.

Another case of a potentially misleading indicator is `dematerialization'. The notion that is popular in some business circles, namely that significant dematerialization of the economy is proceeding more or less spontaneously, suggests that no major policy interventions are needed. However, if the analysis is done properly – admittedly not easy – the opposite conclusion may well be warranted, especially for the `high tech' part of the economy where future economic growth seems likely to be concentrated.

In the economic arena the need is not so much for basic research as for applied research. The crucial question for policy-makers to address is easily stated: how can governments encourage innovations that tend to increase social welfare without resulting in increased demand (which may be indirect, as noted above) for toxic and exergy-intensive materials? More precisely, how far can knowledge-intensive economic activities be de-linked from the underlying infrastructure and capital equipment.

Apart from environmental harm associated with extraction, refining and fabrication processes involving toxic chemicals and elements, it is important to recognize the potential for near term scarcities. The policy implications of potential scarcity are essentially the same as the implications of environmental accumulation, namely that dissipative uses of toxic and/or scarce materials must be restricted.

Wherever possible, economic instruments should be used, either taxes or exchangeable quotas. The purpose would be to create incentives for industry to develop and implement alternative processes and alternative materials. (An example of the latter would be the need for solders that do not utilize lead, and photographic film that does not require silver).

The need for basic research is especially crucial in ecology. There are many questions for which we have, as yet, inadequate answers and no convincing policy responses. Why are codfish becoming scarce? Why are the amphibians – especially frogs – dying out almost everywhere? Why are the wild bees sick? Why are the coral reefs dying? What can be done to alleviate these problems? A related problem pertains to the definition of scarcity in the case of renewable resources, and the determination of `optimal' biodiversity.

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[1] This is true for practical purposes. However, for scientific precision one should note that the three main environmental sinks (air, water, earth) are not in thermodynamic equilibrium with each other. In the case of the earth’s crust, the surface layers – which are exposed to air and water – are also not in perfect thermodynamic equilibrium with the deeper subsurface layers. The surface layers (especially topsoil) consist of highly oxidized minerals plus organic humus, with significant nitrogen and phosphorus content. The deeper layers are somewhat less oxidized. When deeper layers are exposed

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to weathering, sulfide minerals are oxidized resulting in the formation of sulfurous acid (e.g acid mine drainage). Hydrocarbons (buried in silt) also oxidize, releasing carbon dioxide. On the other hand, metallic silicates from igneous rock tend to react (slowly) with carbonic acid to form carbonates and silicon dioxide. (This reaction is reversed when carbonates are subducted into the magma, releasing carbon dioxide which is vented by volcanos.).

[2] The first major postwar assessment of resource needs and availabilities was sponsored by the Twentieth Century Fund, namely "America's Needs and Resources" by J. Frederick Dewhurst (1947). The American Petroleum Institute commissioned a paper by Eugene Ayres of Gulf Oil Co. (uncle of the present writer) entitled "Major Sources of Energy", presented at its meeting on Nov. 9, 1948. After 6000 reprints it was decided to publish a book, entitled "Energy Sources - The Wealth of the World" with Charles Scarlott, of Westinghouse. It was published in 1952. President Truman created the Materials Policy Commission, chaired by William Paley, for which Ayres and his colleagues provided much of the background data. The Commission's report, entitled "Resources for Freedom" was published in 1952. To continue the work of the commission, Resources For the Future Inc. (RFF) was created and funded by the Ford Foundation, also in 1952. RFF sponsored its first major conference in 1953, resulting in a book "A Nation Looks at its Resources" (1954), and many others since then.

[3] A partial list of studies carried out in the US alone during the years 1972 and 1973 includes the following: "Patterns of Energy Consumption in the United States" Office of Science and Technology, Executive Office of the President, January 1972; "The Potential for Energy Conservation" Office of Emergency Preparedness, Executive Office of the President" October 1972; "U.S. Energy Outlook", Committee on US Energy Outlook, National Petroleum Council, December 1972; "Understanding the National Energy Dilemma" Livermore National Laboratory, for the Joint Committee on Atomic Energy, U.S. Congress, Fall 1973 (later updated and republished as "Energy: A National Issue", F. X. Murray, Center for Strategic and International Studies, Georgetown University, 1976); "Energy Facts" prepared by the Congressional Research Service for Subcommittee on Energy, Committee on Science and Astronautics, U.S. House of Representatives, November 1973; "The Nation's Energy Future" A Report to Richard M. Nixon, President of the United States, submitted by Dixy Lee Ray, Chairman of the United States Atomic Energy Commission, December 1973. The massive Ford Foundation Energy Policy Study was also commissioned in 1971, although the publication did not occur until 1974.

[4] There are statistical approaches to addressing the causality issue. For instance, Granger and others have developed statistical tests that can provide some clues as to which is cause and which is effect [Granger 1969; Sims 1972]. These tests have been applied to the present question (i.e whether energy consumption is a cause or an effect of economic growth) by Stern [Stern 1993; Kaufmann 1995]. In brief, the conclusions depend upon whether energy is measured in terms of heat value of all fuels (in which case the direction of causation is ambiguous) or whether the energy aggregate is adjusted to reflect the quality (or, more accurately, the price or productivity) of each fuel in the mix. In the latter case the econometric evidence seem to confirm the qualitative conclusion that energy (exergy) consumption is a cause of growth. Both results are consistent with the notion of mutual causation.

[5] Marx believed (with some justification at the time he wrote) that the gains would flow mainly to owners of capital rather than to workers. Political developments have changed the balance of power since Marx's time. The division between labor share and capital share has been remarkably constant

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over many decades, although the capital share has been increasing in recent years. However, whether the gains are captured by labor or capital does not matter: in either case, returns to energy (or natural resources) tends to decline as output grows. This can be interpreted as a declining real price.

[6] In a recently published economic textbook written by a Harvard Professor, the income allocation theorem is `proved' and illustrated using the example of bakeries producing bread from capital and labor (but without flour or fuel) [Mankiw 1997]. Empty calories, indeed!

[7] Apparently the bimodal distribution is still regarded by most geologists as speculation. It is true that there is no direct evidence of bimodality. However, this is not a serious objection, inasmuch as there is equally no direct evidence for the McKelvey hypothesis of single modality. On the other hand, if copper, lead and zinc were distributed according to the McKelvey rule, the total quantities in the earth's crust must be hundreds or thousands of times greater than the accepted crustal abundance.

[8] A somewhat simpler methodology, known as production history forecasting, involves predicting the future shape of the theoretical production curve from the historical data alone. The `best fit' is then used to predict future production history. This method was systematically applied to all mineral, metal and fuel resources, using U.S. and global data available up to the mid 1970s [Arndt and Roper 1976]. The method does not make use of the additional data (on rates of discovery, proved reserves and so on) used by Hubbert. It is interesting to note that Arndt and Roper's curve-fitting method, using data through 1974, predicted that the peak year would occur in 1984, whereas in fact it had already occurred in 1970. For global production, they predicted a peak in 2034, which now appears very unlikely.

[9] According to a report prepared for the Russian government (and evidently leaked), during the last fifty years 384 reactor accidents have occurred in Russia, that released radiation, resulting in 58 deaths and 214 cases of acute radiation poisoning. In contrast, there has only been one reactor accident that released radiation in France, with no deaths (*Time Magazine* Sept. 18, 2000, p.43).

[10] A US study sponsored by the DOE concluded that `unaccounted for' natural gas losses, calculated as the difference between system inputs and delivered outputs, with an allowance for gas used to operate compressors, amount to 2% on average [Barns and Edmonds 1990]. This figure is consistent with a weighted average of reports from individual distributors [ibid]. A later study by the Stockholm Environment Institute arrived at a slightly (17%) lower estimate, but without specifying the methodology [Subak et al 1992]. The small difference between the US and Europe is probably due to the fact that the US distribution system is, on average, somewhat older.

[11] Athletes have been known to take drugs like EPO that increase the oxygen carrying capacity of the blood; however, too many red blood corpuscles makes the blood thicker and harder to pump, which stresses the heart. This is why such drugs are regarded as dangerous.

Figure 1: Fossil fuel growth engine

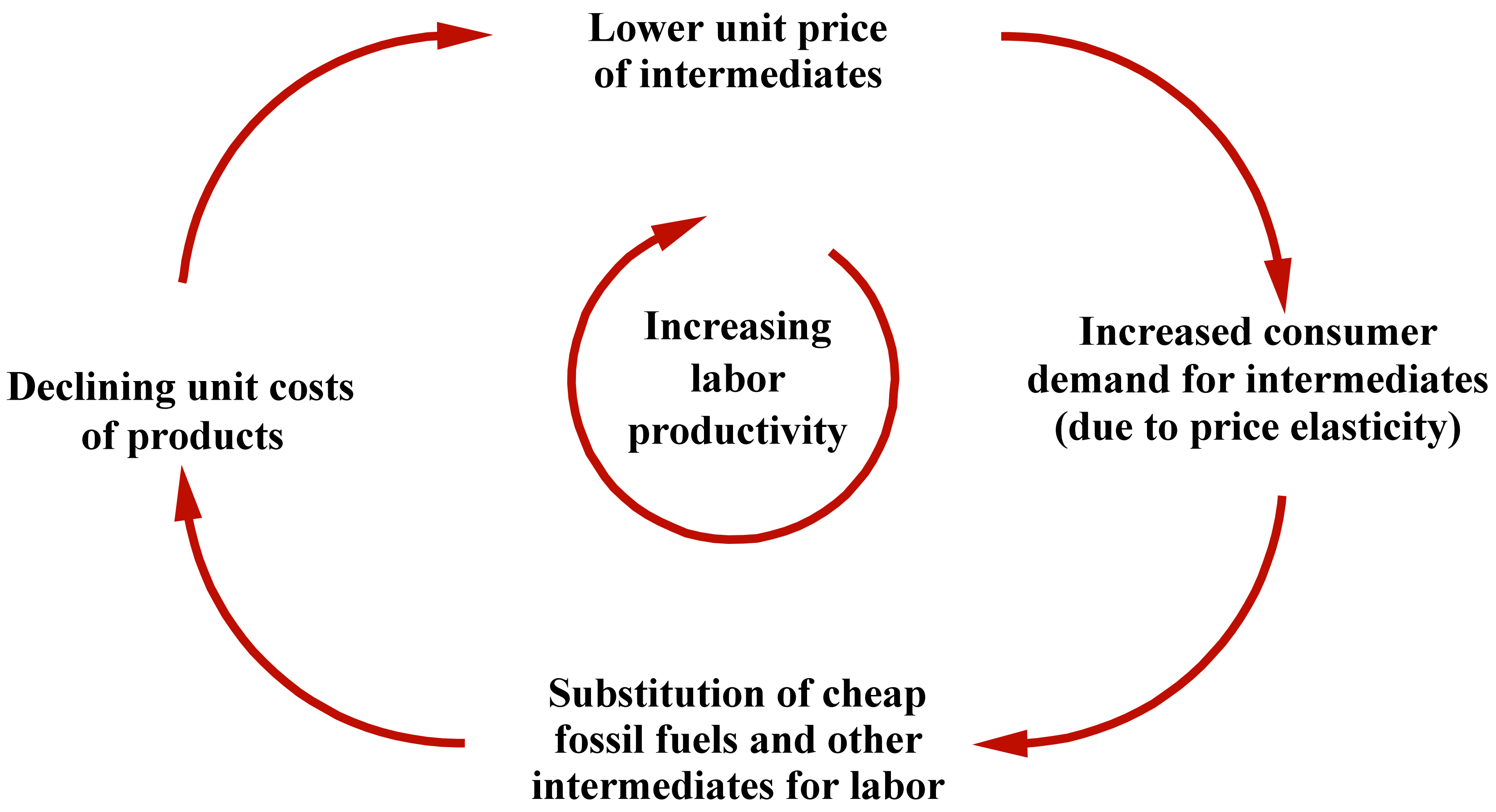
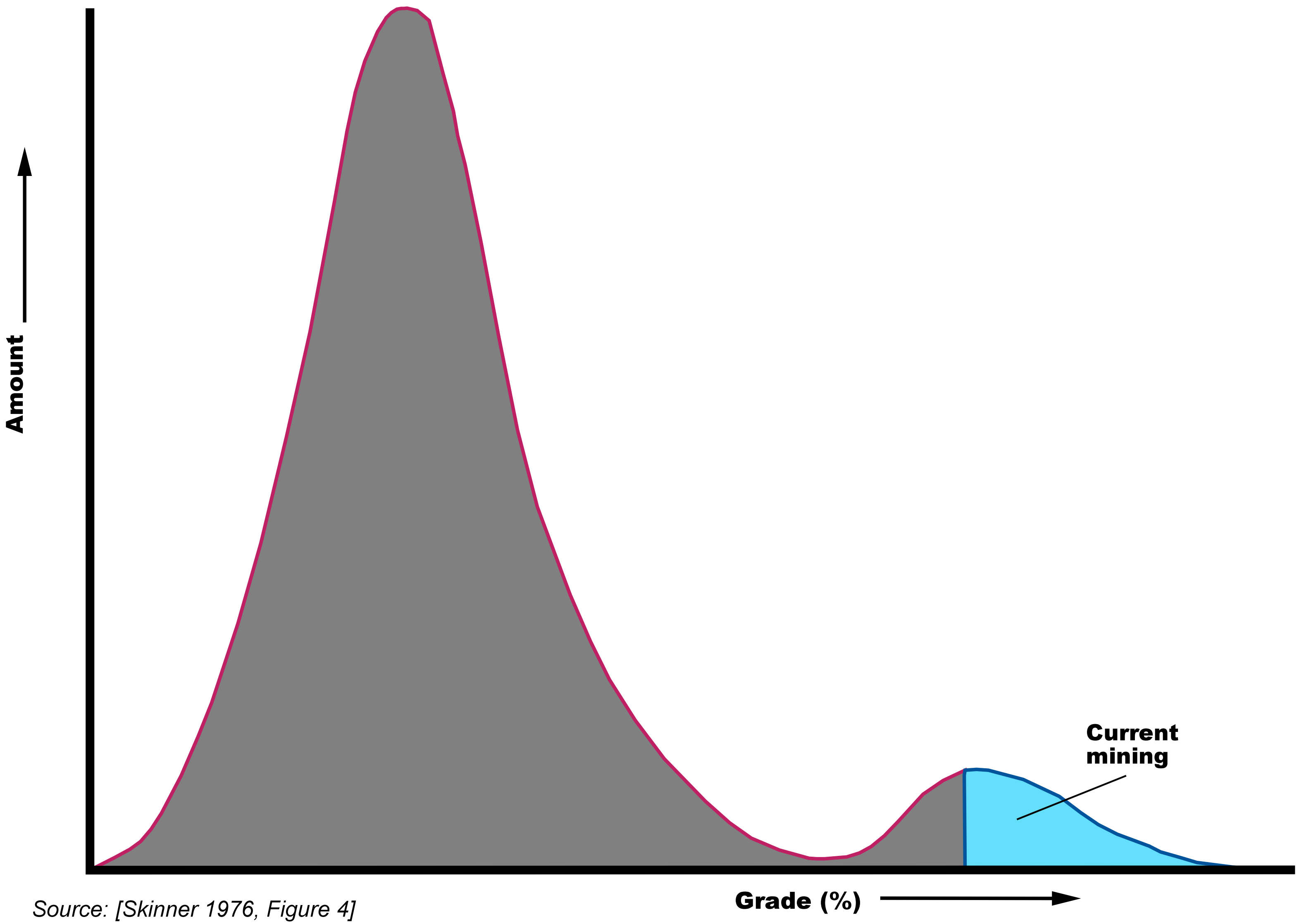
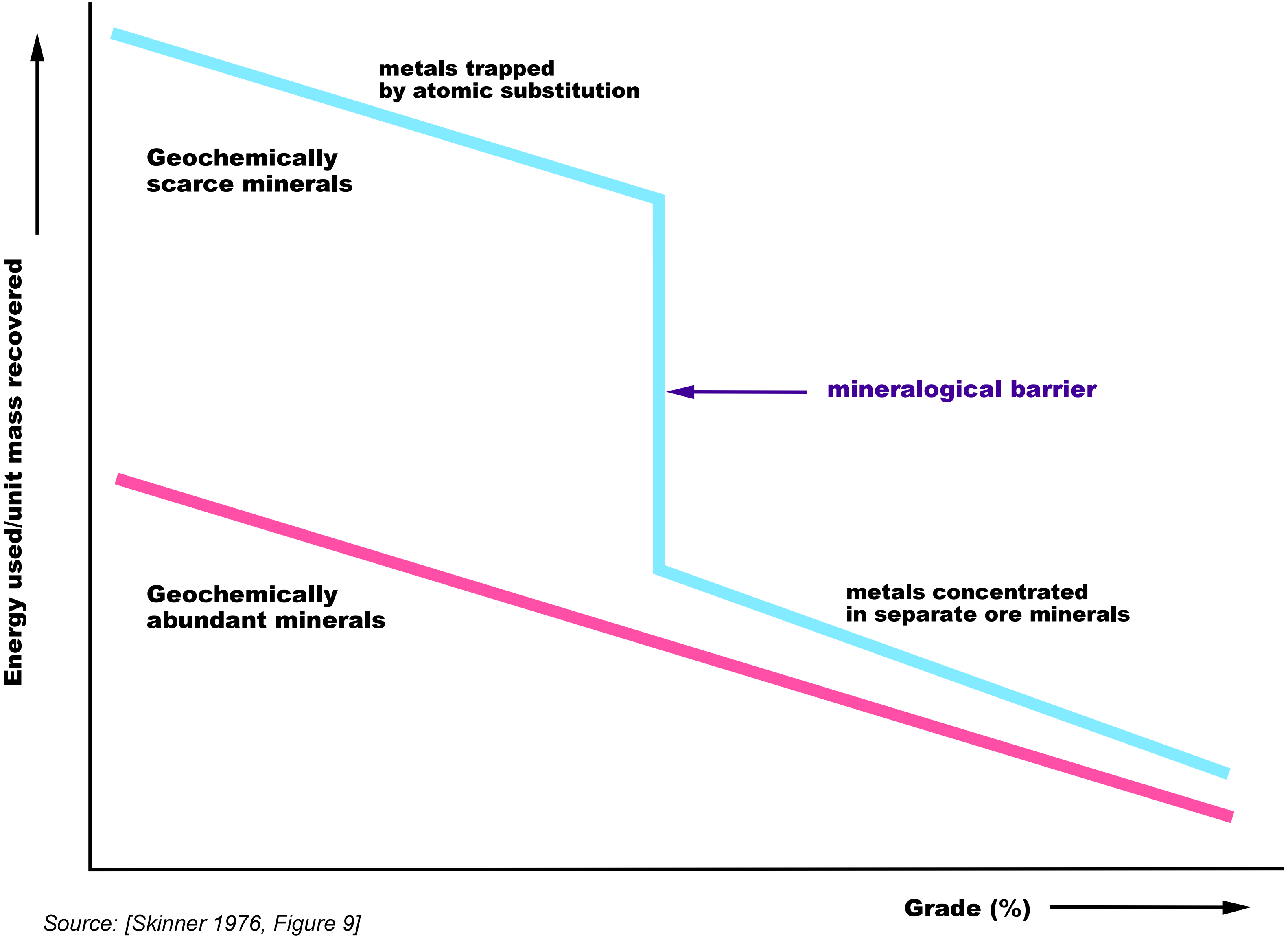


Figure 2: Probable distribution of a geochemically scarce metal in the Earth's crust



Source: [Skinner 1976, Figure 4]

Figure 3: The mineralogical barrier



Source: [Skinner 1976, Figure 9]

Figure 4: Optimum supply of services of nature