PART TWO: ECONOMICS AND ENTROPY

CHAPTER 7

ECONOMIC PRODUCTION AND ITS ECOLOGICAL CONSEQUENCES

7.1 Linking ecological damage to economic production

Chapter 6 recorded a roughly linear growth in human energy consumption from the hunter-gatherer era up to about one thousand years ago. The energy involved was almost exclusively renewable (in the form of biomass) and the by-products of human energy use were all biodegradable. A consequence was that most of the entropy resulting from this energy use was radiated back into space without widespread damage to other creatures on earth. Up to this point in human history, humanity's involvement in the flow of energy through the biosphere did not differ significantly from that of other species.

This seemingly benign profile of human energy use began to change radically around the time of the Industrial Revolution. Humankind's rising energy consumption changed from a linear to an exponential progression (Figures 6.1 and 6.2). An increasing proportion of energy consumed was fossil (nonrenewable) in origin (section 6.8). And increasing quantities of artifacts produced with this energy were not biodegradable. A result was that human energy use began to cause appreciable damage to the biosphere at large.

A general survey of this damage was given in Chapter 5. One highly publicized form of damage is global warming, stemming both from a breakdown in the atmospheric mechanisms that release low-grade heat from the biosphere and from increasing amounts of heat to be released (sections 5.3, 5.4). Another form is the increasing presence in the biosphere of degraded material structure, typified by plastic junk (section 5.5) and by breakdown of the ozone layer (section 5.6). A third is humanly induced loss of biodiversity (section 5.9), which amounts to a serious degradation of the biosphere itself. Damage of these and related sorts by now has become so severe that, in the sober judgment of many trained observers, the biosphere is on the verge of losing its capacity to support humanity as we currently recognize it.

Several factors in the network of causes leading to this predicament have already been examined. One is the rapid increase in human population over the past few centuries (Figure 6.2). As long as per capita energy-use holds constant, more people using energy obviously results in more energy being consumed overall. As we shall see, however, there are respects in which increased population follows from increased energy use rather than vice versa. Further consideration of the population factor is reserved for a subsequent chapter.

Another factor behind humanity's rising level of energy use is the rapid increase in per capita energy consumption shown in Figure 6.1. Looking ahead to concerns of the present chapter, there are several things to note about this particular factor. One is that the increase in question probably could not have been achieved without extensive use of fossil fuel. As already indicated (section 6.8), fossil fuel consumption grew about 12 times more rapidly during the 20th century than did use of renewable energy. Even if human population had been arrested at its 1900 level (the approximate point at which fossil fuel surpassed biomass fuel consumption), the increase in per capita energy use during that period would have required more energy than was available from renewable sources alone.[1]

This means that the exponential rise in per capita energy consumption following the Industrial Revolution played a substantial role in triggering many of the harmful effects of unexpended entropy examined in Chapter 5. Recall once again that global warming, destruction of the ozone layer, the accumulation of plastic junk, and the widespread poisoning of other species are particular examples of these effects. An obvious consequence is that our current level of per capita energy consumption is at least partially responsible for the current plight of the biosphere upon which human existence depends.

Yet another fact to bear in mind is that our present level of per capita consumption is due primarily to the economic production of the world's most highly developed countries. The average person in one of the world's less developed nations typically consumes only a small fraction of the energy used per capita in highly developed countries like the U.S. and Canada. Generally speaking, a country is classified as developed or undeveloped according to its per capita income (http://en.wikipedia.org/wiki/Industrialized_country). This suggests that a country's per capita income is more than randomly associated with its per capita energy use.

A country's per capita energy use, of course, is its overall energy use divided by its population. These observations about per capita energy use are snippets from a larger picture relating economic productivity to energy consumption generally. The underlying fact of the matter is that a country's overall income tends to correlate positively with its fossil energy consumption. Although the correlation is not linear (the way x and y are linearly correlated in '$x=2y$', for example), countries with relatively high national incomes tend to generate relatively large amounts of ecologically damaging entropy.

The economic aspects of the big picture appear even more problem-laden in light of the common view among orthodox economists that economic health goes hand in hand with economic growth. According to the orthodox view, the sign of a well functioning economy is its ability to maintain growth at a rate (say between two and five percent) that avoids both recession and inflation. But as just noted, growth in income generated is positively correlated with increased consumption of fossil energy. From an ecological perspective, accordingly, the long-term upshot is that the very process of maintaining the health of an economy (according to this view) makes the biosphere that supports that economy progressively unhealthy. This upshot, to say the least, appears counterproductive, and as such, calls for dispassionate examination.

Part I of this study (chapter 1 through 6) was taken up with an analysis of the ecological factors underlying our current environmental predicament. Part II is given over to an investigation of relevant economic factors in turn. We begin in the present chapter with the connection between energy consumption and economic growth.

7.2 Energy use correlated with GNP

[Technical addendum. When economists speak of economic growth, they typically are talking about an increase in either Gross Domestic Product (GDP) or in Gross National Product (GNP). Simply stated, GDP is the total market value of goods and services produced within a country during a standard accounting period, and GNP is GDP plus (i) income of domestic residents from abroad minus (ii) domestic income earned by non-resident foreigners. These measures are commonly regarded as indices of a nation's economic performance. As such, they are useful both in comparing different economies and in gauging achievements of a given economy in different time periods. Different reporting practices in different countries require that both measures be kept in use.

Neither measure makes allowance for fixed capital (equipment, buildings, inventories) used in production. When capital expenditure is taken into account, it can be subtracted from GNP to obtain Net National Product (NNP). Another adjustment sometimes made is to subtract the portion of market price due to taxes, thus converting NNP into National Income (NI). For some purposes, economists find it appropriate to compare economies in terms of GNP *per capita*. This more discriminating measure is often used in comparing economic conditions between developed and developing countries, inasmuch as the latter tend to be more heavily populated.]

An often-reproduced set of statistics was released by the U.S. Office of Science and Technology (OST) in the early 1960s showing a close correlation between annual per capita energy consumption and per capita GNP (in 1968 dollars) for more than 40 countries worldwide. The following chart shows the correlation for a representative sample of countries.[2]

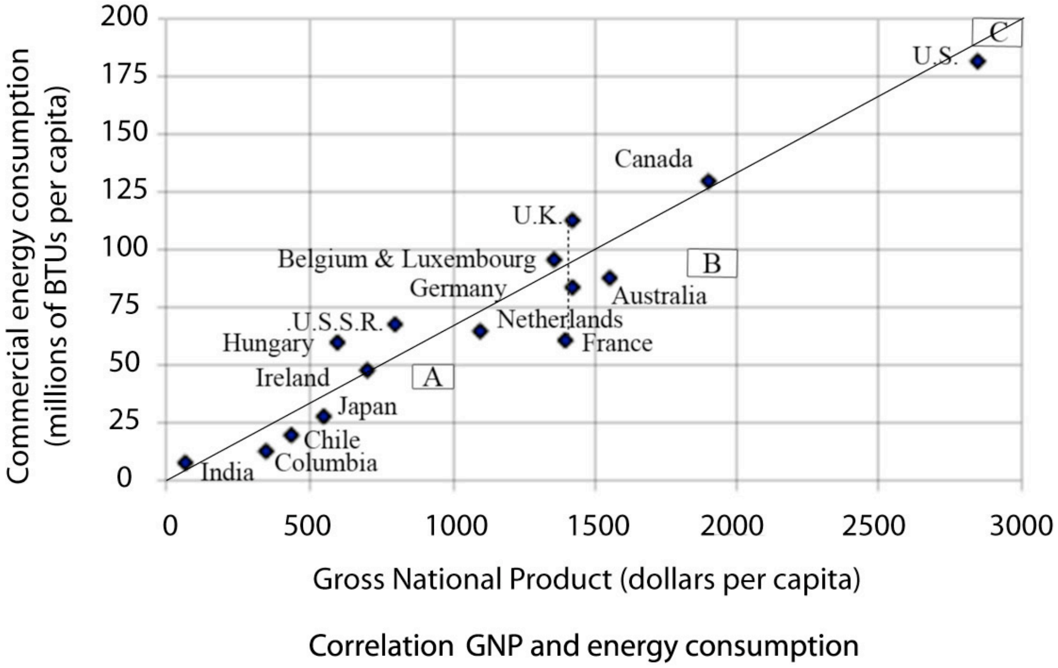

Chart 7.1

The chart is divided into three zones, in order of increasing levels of energy consumption. Zone A includes countries with less than 50 million BTUs per capita annual energy consumption at that time and less than $1,000 per capita GNP. Zone B includes countries not in zone A with less than 100 million BTUs energy consumption and less than $2,000 GNP. Zone C includes countries in neither zone A nor zone B, all of which have per capita energy consumption levels of over 100 million BTUs. These zones will be discussed in reverse order.

Zone C is occupied by the three countries then ranking highest in commercial energy consumption worldwide, the U.S., Canada, and the U.K. The U.S. is characterized by about 180 million BTUs of energy consumption per person and about $2,850 per capita GNP. This gives it an energy-in to GNP-out ratio of approximately 60,000 to one (rounded off to the nearest 5,000), which is to say that each dollar of goods and services produced requires an average consumption of about 60,000 BTUs of energy. Let us refer to this as the country's "(energy) conversion ratio."[3] The corresponding ratios of Canada and the U.K. are roughly 70,000 and 80,000 respectively. The average per capita ratio for these three countries thus is about 70,000 BTUs for each dollar GNP.

Zone B contains 14 countries figuring in the OST statistics, of which 7 are shown in the chart above. The 7 countries shown constitute the approximate center of an otherwise nebulous cluster. On the left side of the cluster are South Africa and Poland (neither shown) with conversion ratios of about 150,000 and 130,000 respectively. On the right are Finland and New Zealand (neither shown) with ratios respectively of about 35,000 and 30,000. The average ratio of the cluster of 14 countries is close to 70,000, which is also the average ratio of the 7 countries shown. In this respect, the countries shown are representative of the entire cluster.

Zone A includes 27 countries, most of which were then designated "developing" by World Bank criteria. With a few exceptions, these are all close to the axis identified by the 5 countries shown in the chart. The average conversion ratio for the group shown is about 60,000 BTUs per dollar GNP, the same as the average of the 27 countries in zone A taken together. The highest ratio in this zone, standing at approximately 80,000, is shared by Yugoslavia and Romania (neither shown). Ghana (not shown) has the lowest ratio at about 20,000.

The solid line drawn from lower left to upper right corners of the chart indicates a ratio of 66.67, which in the context of the chart rounds off to 65,000 BTU for each dollar

GNP. This line thus splits the difference, as it were, between the average conversion ratio of 70,000 for zones B and C and the 60,000 ratio of zone A. As a glance at the chart should reveal, the line pulls all the data represented on the chart together into a reasonably coherent pattern. On the average worldwide, production of one dollar's worth of goods and services in the early 1960s consumed about 65,000 BTUs of energy.

In one ordinary sense of the term, systems of production can be rated as more or less efficient according to the quantity of energy they require to produce a given amount of goods and services. The ratios of BTUs-in to GNP-out indicated above thus serve as measures of comparative efficiency of the productive systems concerned. A number of interesting conclusions in that regard are supported by the OST data upon which Chart 7.1 is based.

One conclusion pertains to the dotted line drawn vertically between the entries on the chart for the U.K. and France. In the early 1960s, these two countries had about the same per capita GNP, an amount approximated by Germany and Belgium/Luxembourg as well. But France (with a ratio of 40,000) produced that amount with less energy and hence more efficiently than Germany (with 60,000), which in turn did so more efficiently than Belgium/Luxembourg (with 70,000), which latter did so more efficiently than the U.K. (with 80,000). Although the reasons for these disparities undoubtedly are many and various, they should be worth studying by anyone interested in energy conservation on a national level.

Another potentially interesting fact is that the 27 countries occupying zone A had an average ratio of 60,000, in comparison with an average of 70,000 for the 17 developed nations in zones B and C. This at least suggests that the process of development carries with it an overall loss in energy efficiency. A contrasting observation, however, is that gain in productivity is not incompatible with increased energy efficiency, as witnessed by the comparative conversion ratios of the U.S. (60,000) and the U.K (80,000).

It is also interesting to note that both the most and the least energy-efficient countries in the study fall in zone B. The least efficient is South Africa, with a conversion ratio of about 150,000. The most efficient is New Zealand, with a ratio of about 30,000.

7.3 Factors affecting a country's conversion of ratio (energy in/GNP out)

Chart 7.1 shows an average conversion ratio of 65,000 for the 15 countries specified. In this respect, these countries were representative of the entire group of 40 countries in the OST survey. This means that in the early 1960s the 40 countries involved consumed an average of about 65,000 BTUs of energy for each dollar per capita of GNP their economies produced.

For present purposes, there is nothing special about the early 1960s other than its being a time for which such data are readily available. Neither is there anything especially significant about 65,000 as the average conversion ratio during that period.[4] Different ratios would be expected to emerge from analyses of other periods of recent economic history.

This is so for a variety of reasons. One obvious reason is fluctuation in energy costs. As the price of oil increases, for example, economies relying heavily on petroleum products will tend to use them in more efficient ways. Efficiency in this case amounts to more goods and services being produced with the expenditure of a given amount of energy.

Another reason for change in a country's conversion ratio is variation in the proportion of its GNP contributed by its service sector. As a general rule, services like education, health care, and entertainment are less energy intensive than industries dedicated to the manufacture of goods. It follows that an economy's conversion ratio will generally improve with an increasing proportion of services represented in its GNP.

A further reason has to do with changes in production techniques that take place as an economy evolves toward more fully developed status. In connection with Chart 7.1, it was noted that developed countries tend to have higher conversion ratios (are less energy efficient) than their counterparts in the developing world. This appears to be no accident. As labor-intensive productive practices give way to industrial modes of production, it should be expected that the economy in question becomes more energy intensive.[5] The price of increased energy intensity typically is an increase in energy (compared with labor) expended in producing a given amount of goods.

Despite the current drift toward increased industrialization on the part of developing countries, however, economic production worldwide has grown more rapidly over the past several decades than has consumption of energy for commercial purposes (http://www.theaustralian.news.com.au/story/0,20867,19620601-36375,00.html). This is due in part to the fact that developing countries accounted for less than half of total global energy consumption during that period (ibid.), and in part to more efficient energy use on the part of developed economies. Yet another cause of this growing efficiency is a general shift from lower to higher quality energy sources, in particular a shift from coal to electricity and natural gas.[6]

Take the case of China by way of illustration. In the approximately 20 years (1977-1995) following the end of its revolutionary period, China's GNP grew annually at an average of over 9%. During the same period, however, its reported energy use per unit GNP fell a remarkable 55% (back to the 1957 level before its growth spurt began). This increase in energy efficiency is attributable in part to increasing imports of energy-intensive products. But it was a result also of advances in technology and of increased specialization. Another key factor was the growth of its service sector from 24% to 31% of its total GNP.[7]

This recent pattern of economic production growing more rapidly than energy consumption worldwide suggests several attitudes toward energy use that might be adopted by economic planners in individual countries. A country might try to hold its GNP constant while decreasing its consumption of energy; or it might try to hold its energy use constant while increasing its GNP. As the case of China indicates, moreover, it might even aim to decrease its use of energy while increasing its GNP. Up to a point, any one of these strategies might conceivably be feasible.

But only up to a point. In this respect, attempts to get more and more economic production per unit energy by increased energy efficiency are like athletes trying to lower the record for the 100 meter dash by improved diet and conditioning. At some point not far from the present record, human beings just won't be able to run any faster. Similarly, at some point not very far from the current performance of our more efficient economies, it will no longer be feasible to achieve increased economic output without expending more energy. From that point onward, continued economic growth will come only at a cost of increased energy expenditure.

Once again, there is no long-term significance in the fact that the average conversion ratio for 40 countries in 1961 was about 65,000 BTUs of energy per dollar GNP. What is significant for present purposes is the realization that producing a given unit of GNP always involves the expenditure of a non-trivial amount of energy. In all economies affected by the Industrial Revolution, regardless of their current state of development, the production of wealth invariably is tied to the consumption of energy. Given resources currently available, moreover, the energy consumed in economic production is bound to include a substantial component of fossil fuel.

7.4 The entropic residue of economic production

Let us take a broader look at the relation between energy consumption and economic production. Among other functions, a nation's economy generates benefits for the society it serves. Among these benefits are the goods and services that contribute to its GNP. In later chapters we will consider whether there are economic benefits that cannot be measured in quantitative terms. For now we are concerned only with benefits included under GNP (or GDP, etc.).

These benefits are produced out of, and with the help of, resources taken from the biosphere. Included among such resources are water, minerals like iron and copper, gases like oxygen and nitrogen, and various forms of energy. In the terminology introduced in Chapter 2, these resources are all forms of negentropy. Let us refer to them generally as *ecological capital*. Since expenditure of such resources is necessary in the production of economic benefits, moreover, we may speak of that expenditure as the *negentropic cost* of the benefits in question.

The negentropic cost of economic production has an entropic counterpart. As defined in Chapter 2, negentropy is the opposite (the negative) of entropy, and of course vice versa. Expenditure of negentropy thus generates an equivalent in entropy. We may refer to this as its *entropic residue*. Just as the negentropic costs of production include the minerals, fuels, and liked resources expended in the process, so the entropic residue includes all the various forms of entropy generated by that expenditure. As a consequence of the Second Law of Thermodynamics (Chapter 1), negentropy entering the economic process exits in the form of entropy.

By way of parallel, recall the thermodynamic description of living organisms laid out in Chapter 3. An organism maintains its life process by "sucking up" negentropy from its environment and by ridding itself of the resulting entropy for the environment to dispose of. In the case of individual organisms, the negentropy in question consists mainly of energy and nutrition, whereas the expelled entropy consists largely of waste materials and low-grade heat.

When human beings band together and engage in economic activity, however, other forms of entropy and negentropy become involved. Negentropy “sucked up” from the environment comes to include energy in forms other than sunlight and foodstuffs, along with minerals and other natural resources. At this stage in economic history, unfortunately, the resulting entropy has come to include global warming, a decimated ozone layer, and the disruption of natural cycles essential to life (Chapter 5).

There are parallels with the flow of energy through ecosystems as well. A healthy (normally functioning) ecosystem replaces negentropy consumed by its constituent organisms by new supplies from outside sources (mainly solar radiation), and passes off the resulting waste products (mainly waste heat) for more comprehensive ecosystems to dispose of. An ecosystem remains healthy as long as the negentropy it takes in and the entropy it discharges remain in approximate balance.

By definition, the biosphere is the most comprehensive ecosystem of all. This means that it is the system into which all other ecosystems discharge their entropy and from which the entropy accumulated from all life on earth is passed off into space. The health of the biosphere over the long term depends upon its ability to maintain an approximate balance between the negentropy consumed by its resident organisms (primarily as sunlight and, recently, as fossil fuel) and the entropy resulting from this consumption that is radiated into space as low-grade heat. The entropy that must be disposed of in this fashion includes both entropy generated by biological processes and, in recent centuries, that generated by economic activity.

As long as the biosphere remains healthy, it is able to get rid of most of the entropy stemming from these two sources as a matter of course. In preindustrial times, the entropic by-products of economic production were not exorbitant and the biosphere was able to accommodate them without undue stress. Within the span of the 20th century, however, constantly expanding economic production has resulted in an accumulation of vast amounts of entropy which the biosphere has been unable to discharge into space. The inevitable result is a disruption of its thermodynamic balance (solar energy in, low-grade heat out) that throws into doubt the biosphere's continued ability to support its top consumers (Chapter 4).

Conventional wisdom takes it for granted that economic health requires constant growth in the production of goods and services. If so, then economic health and the health of the biosphere cannot be maintained simultaneously. We will be concerned with this conflict and ways of moderating it throughout the next several chapters of this study. By way of preparation, we should consolidate the results of the present chapter.

7.5 A disregarded economic principle

During the midpart of the 20th century the correlation between energy consumption and GNP remained controversial, with mainstream economists generally reluctant to admit more than a coincidental relation.[8] Recent economic studies, however, have demonstrated a remarkably close interaction between the two. The results of these studies support our conclusion in section 7.3 that production of a given unit of GNP requires the expenditure of significant amounts of energy.

One study published in 1982, for example, showed a tight year-by-year correlation between GNP and energy use in the U.S. from 1870 to 1981, a correlation that extended even to minor yearly fluctuations.[9] Another study reported in the 2003 paper "Energy and Economic Growth," (by David Stern, an ecological economist[10] at Rensselaer Polytechnic Institute) concluded that "there is a very strong link between energy use and both…economic activity and economic growth." In yet another example, Martin Wolf (chief financial commentator for *Financial Times*), in 2006, characterized the close correlation between rise of the gross global product in the 20th century and that of global energy consumption as “eerie” (http://www.ufppc.org/content/view/4731/2/).

A consequence of this tight coupling between economic production and energy consumption is that the production of economic goods unavoidably generates entropy. This consequence is formally demonstrated by the following inference:

(1) The production of economic goods consumes energy
(2) The consumption of energy generates entropy
Therefore, (3) The production of economic goods generates entropy.

In (1) and (3), the expression ‘economics goods’ is intended to cover services as well as material products. The general sense of the expression here is that of economic benefit or economic utility.

This inference is obviously valid, which means that the truth of conclusion (3) necessarily follows from the truth of premises (1) and (2) (i.e., the premises entail the conclusion). The truth of (1) is shown by considerations summed up in section 7.3, as well as by studies like those mentioned earlier in this section. The truth of (2) follows from the Second Law of Thermodynamics. Since the inference is valid and its premises are true, the inference establishes the truth of its conclusion.

By itself, the conclusion that economic production gives rise to entropy seems unremarkable. Entropy results whenever energy is consumed. The conclusion is cast in a more ominous light, however, by the fact that most of the energy used in economic activity today comes from fossil fuels.[11] In ways discussed at length in Chapter 5, entropy deriving from fossil fuels often shows up in some form of ecological damage (global warming, habitat destruction, etc.). Under these circumstances, the consequence to note is not just that economic production results in entropy, but that it results in various forms of ecological damage.

The previous inference should be augmented accordingly. Given the present stage of global industrialization, involving massive consumption of fossil fuel,

(4) Entropy generated by economic production by and large is ecologically damaging.

Therefore, (5) The production of economic goods by and large is ecologically damaging.

The truth of (5) follows from the truth of (3) and (4). Thesis (3) is established by the previous inference, and thesis (4) rests on considerations such as those in Chapter 5. Taken together, these two inferences establish the conclusion that, under present circumstances, economic goods come at a cost of ecological degradation.

This result can be expressed in various ways, highlighting different aspects of the ecological expense in question. Interpreted in terms of costs and benefits, the result says that, under current conditions, the ecological cost of economic benefits carries with it a substantial entropic liability. In terms of utilities and disutilities, it says that economic utility implicates ecological disutility on the part of the supporting environment. In thermodynamic terms, it means that economic activity transforms ecological negentropy (energy and structure) into economic negentropy (goods and services), leaving a residue of damaging entropy (low-grade heat and structural disorder) for the biosphere to cope with. However put, the upshot is that current economic production imparts damage to the biosphere.

Let us repeat the conditions under which this conclusion applies. We are not talking about economic growth in all times and circumstances. In eras when only renewable energy is used in economic production, and when goods produced are all biodegradable, economic activity might generate relatively little long term ecological damage. Economic production would still have ecological costs, but this expenditure would not result in a continuing environmental deficit. A healthy biosphere can replace the negentropy extracted from it for economic (or other) purposes. Even with extensive reliance on fossil fuel, moreover, there are circumstances in which additional production can be achieved without additional energy use (consider China in the late 20th century; section 7.3). The additional goods produced in this case might come without additional environmental cost.

The conclusion also needs to be more specifically stated. Economic production, of course, is quantitatively measurable (e.g., so many dollars worth of output per person). But nothing has been said so far about quantities of ecological damage. In this regard, it should be recalled that the damage in question notably includes low-grade heat trapped within the atmosphere, accumulation of plastic junk, and decreased species diversity in the biosphere. All these are forms of entropy subject to quantitative measurement.

Ecologically damaging entropy is also illustrated by breakdown of structure, such as destruction of the ozone layer and disruption of the nitrogen and carbon cycles. Structural breakdown is a form of disorder; and as shown in the Appendix to Chapter 2, disorder also is subject to quantitative measurement. Although not always gauged in calories or inches, structural order and disorder are measurable quantities nonetheless. Let us say that they are measurable in principle.

With this in mind, we may state conclusion (5) in somewhat more concrete terms. With applicable qualifications taken into account, the conclusion may be reformulated as follows:

(P) The production of a given amount of economic goods introduces a corresponding amount of ecological degradation.

The corresponding amount will vary with case and circumstances. And in individual cases, it will often be hard to measure exactly. But given our massive reliance on fossil fuel, that amount in any given case is unlikely to be negligible.

Result (P) has the status of an economic principle. It is economic in the sense that it applies to industrialized economies. It has the status of a general principle because it applies to such economies generally, regardless of their geography or stage of development. The fact that nothing like it can be found in standard economic textbooks does not deprive it of this status.

Principle (P) state, in effect, that a certain measure of ecological capital must be given up for every dollar unit of economic production. This principle will figure prominently in the discussion of the following chapters.

Notes

1. World population in 1900 (about 1.6 billion) was approximately 1/4th that in 2006 (about 6.5 billion). If population had held steady at the 1900 level during the 20th century, while per capita energy use increased at its actual rate, present total human energy consumption would be ¼ of its actual amount today. In 1900, total energy use was equally divided between biomass and fossil fuel (section 6.8); count those amounts as one unit each. During the 20th century, use of biomass energy approximately doubled while use of fossil energy increased 20 fold. This makes 22 units total human energy consumption in 2006. One-quarter of this amount is 5.5 units. With only 2 units contributed by biomass, the remaining 3.5 units would have to come from fossil sources. Even if world population had remained steady at the 1900 level, actual increases in per capita energy use by 2006 would have been divided into about 35% biomass and 65% fossil.

2. The study from which these data derived was made in 1961. Similar treatments of these data can be found in H.T. Odum, *Environment, Power and Society* (Wiley-Interscience, New York, 1971), 184; *Scientific American*, Sept. 1971, 142; and *The Limits to Growth*, by D.H. and D.L. Meadows, J. Randers, and W.W. Behrens III (Universe Books, New York, 1972), 70.
3. Other terms designating comparable measures in economic literature are “economic productivity,” “energy efficiency,” and “energy intensity.” The higher a country’s energy conversion ratio, the lower its energy efficiency.
4. A substantially lower ratio for the U.S. economy in 1960 is recorded in *The Concise Encyclopedia of Economics* (http://www.econlib.org/LIBRARY/Enc/Energy.html). A somewhat higher value (adjusted for inflation) is reported by the U.S. Department of Energy (http://www.eia.doe.gov/emeu/aer/txt/ptb0105.html). Different values also result when GDP replaces GNP in the statistics.
5. In a recent comparison of the 40 economies with highest GDP in 2004, with respect to per capita productivity (high, moderate, and low) and energy efficiency (high, moderate, and inefficient), two-thirds of the economies with high or moderate energy efficiency were low in productivity and none of the economies with high or moderate productivity was high in energy efficiency (http://en.wikipedia.org/wiki/Image:Gdp-energy-efficiency.jpg).
6. See “Energy and Economic Growth,” by David I. Stern, Department of Economics, Rensselaer Polytechnic Institute, April 2003. As already noted in section 6.8, during the 20th century global use of coal increased by a factor of five, compared with a 280 fold increase in the use of natural gas. During the same century, use of electricity increased about 1000 times (Smil, *Energy*, 186).

7. Statistics in this paragraph come from the *China Statistical Yearbook 1992* (China Statistical Press, Beijing) and from recent reports of Japan's Central Research Institute of Electric Power Industry (CRIEPI). China's economic growth has continued at about the same rate (9%) up through 2006 (http://www.chinability.com/GDP.htm). Due in part to its very large population, this growth has been achieved at a fraction of U.S. per capita energy consumption (http://www.eia.doe.gov/emeu/cabs/chinaenv.html).
8. An account of the controversy is given in J. Darmstadter, J. Dunkerly, and J. Alterman, *How Industrial Societies Use Energy: A Comparative Analysis* (Johns Hopkins University Press, Baltimore, 1977).
9. See *Beyond Oil: The Threat to Food and Fuel in the Coming Decades*, by J. Gever, R. Kaufmann, D. Skole, and C. Vorosmarty (Ballinger Publishing Company, Cambridge, MA, 1986), p. 82.
10. The differences between ecological and mainline economics are discussed in Chapter 12.
11. As already noted, data presented in section 6.8 shows that use of renewable energy (mostly biomass) doubled during the 20th century while use of fossil fuel increased 20 fold. With a small portion of nuclear energy factored into the mix, this means that fossil sources account for close to 90% of worldwide energy use today. Whether industrial or domestic, most of this use would be classified "economic."