Biophysical Economics: The Material Basis

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In our first chapter, we provided a review of how modern (neoclassical) economics operates as a social science-based means of allocating "scarce" resources, including the philosophy behind the assumptions that govern the operation of that model of how economies work. In this approach markets are seen as especially important as a means of making economic decisions and guiding the allocation of productive resources.

▶ Chapter 2 reviewed earlier approaches to economics, many of which were based on a more explicit understanding and acknowledgment of the biophysical basis of real economies. Thus, while most people who do think about economics today probably believe that the conceptual model (neoclassical circular flow model) that dominates economics is the only possible and proper way to think about economics, there are many alternatives. In fact, as was obvious from ▶ Chap. 2, there are many very different ways we can think about economics that accurately describe at least some important aspects of what is going on in real economies. We just happen to live in a time when there is a dominant form that excludes other world views of what constitutes economics.

Many criticisms have been leveled at this dominant "neoclassical" model. ▶ Chapter 3 undertakes a thorough and damning review of the many problems that exist with the intellectual basis of conventional economics. It focuses specially on the conceptual and logical problems that arise from assuming that economics should be based only on the social sciences even while the basis for actually existing economies is the production and transport of goods and the provisions of services, all of which must take place in the real world of matter and energy and hence are best studied using the natural sciences. Professional economists as a group tend to be uninformed about, or uninterested in, the criticisms that have been leveled at their discipline. In a sense, they have been successful at circling their wagons to protect their core beliefs, ignoring the criticisms, and proceeding with their craft, independent of the criticisms or the degree to which it is or is not successful in describing reality or making predictions.

In the next two chapters, we introduce the reader to another equally or, we believe, more appropriate and accurate approach to economics—biophysical economics. The concept has a very old history, starting with the recognition by whatever might have passed for economists in the Stone Age that one's material well-being depended upon nature and those things that humans might be able to extract from nature and the difficulty or ease in doing so. As humans eased into the first stages of agriculture, we know that they paid a great deal of attention to the material conditions of their economic life due to the large part of whatever wealth they had that was "invested" into observatories, temples, and activities that attempted to understand and beseech their gods to provide rains, good harvests, and so on. The people may not have understood well the forces that generated or not their economic production, but they knew them as important. The work of Anthony Aveni, for example, has led to an entire new discipline of archeoastronomy. He has shown convincingly that entire cities (such as the area around the temples of the sun and moon in Mexico) were constructed to determine the movement of the sun relative to the Earth, leading to a better understanding of planting times.

While we cannot interview such people, as they are long dead, we can examine (or could until recently) the various cultures around the world that are little touched by industrialization to see how they operate. Do they in fact operate in a way consistent with the assumptions of modern neoclassical economists? When the anthropologist Karl Polanyi undertook an examination of a large series of preindustrial "folk" societies, he found that while market transactions had always existed, most people traded their surplus goods [1]. Things were not produced specifically for sale, and markets did not form prices. Societies allocated what we now call goods and services by means of trade, reciprocity, and redistribution. In other words, economics was based more on their material basis than on money. We call this material basis "biophysical economics."

4.1 Background to Biophysical Economics

As we stated in the first sentence of the introduction to this first section, economies exist independently of how we perceive or choose to study them. Also, we noted that economists have chosen over the past 150 years—for more or less accidental reasons—the social sciences and an inappropriate and overly simplified analytical model borrowed from physics as the essential

conceptual base for undertaking our definitions and analyses of economies and economic systems. This is the case, even though actual economies are as much about biophysical as social activities. Actually existing economies must be based on many things, including the physical materials and the energy required to provide goods and services as well as the NCE-sanctified market interactions that transfer these goods and services from firm to household or household to firm. This was well understood by earlier physiocratic and classical economists. Curiously, starting in the 1870s or so, economics somehow became *only* a social science, and it has remained that way for the most part. In this social science-based model, the material world is represented only by the prices of things within the material world.

4.2 What Is Biophysical Economics?

Biophysical economics is a system of economic analysis that is based on the biological and physical properties, structures, and processes of real economic systems as its conceptual base and fundamental model. It has two components: biophysical science itself and economic analysis that is consistent with science and other social sciences such as psychology and anthropology. It acknowledges that the basis for nearly all wealth is nature and views most human economic activity as a means to increase (directly or indirectly) the exploitation of nature to generate more wealth. As such, it focuses on the structure and function of real economies from an energy and material perspective, although it often considers the relation of this structure and function to human welfare and to the money (i.e., dollar) flows that tend to go in the opposite direction to energy [2]. From a biophysical perspective, one's job is viewed as trading one's time at work (the monetary value of which is related to the energy flows of society controlled by the individual) for access through wages and salaries to the energy flows of the general economy. This "general economy" contains goods and services created from the extraction of energy from the earth in anticipation of some demand for them. At present, each dollar we spend requires roughly 5 megajoules (about half an 8 oz. coffee cup's worth of oil or equivalent energy) to generate the good or service purchased. With economic inflation, the energy per dollar decreases over time so that in 1970, one could receive about ten times more energy (as used to generate goods and services) per dollar than he or she can today. The ice cream that fueled Hall's paper route in 1954 cost only 5 cents, but required for its production roughly the same amount of energy as today. A biophysical economist might ask "how many minutes of labor did you have to put in to earn that nickel? At your current salary, do you put in more or fewer minutes for that ice cream cone? If your salary is high, is it commensurate with the energy flow in society that you control?" Or perhaps "when you spend your salary, how much of the world's nonrenewable resources are depleted, and how much did you contribute to changes in the atmosphere?"

Figure 3.1 is the "firm and household" diagram said to represent the economy in most introductory economics textbooks. We find this model, which represents the basis of most economic theory and teaching, to be less than useful in representing the real things that must occur within a real economy. As developed in Hall et al., this representation violates the laws of thermodynamics (which nothing real can do), has completely inadequate and incorrect boundaries, and has not been tested using the scientific method [3]. Our perception of the simplest diagram that one could use to represent a real economy, which is far more complex and infinitely more accurate than Fig. 3.1, is Fig. 3.3. This diagram, and real economies, includes (from left to right) (1) energy sources (principally, the sun) that are essential for any economy; (2) the material that circulates upon the earth's surface through natural and seminatural ecosystems; and (3) the human-dominated steps of exploitation, processing, manufacturing, and consumption. Blue and yellow arrows show the transfer of materials and energy through the economy. Raw materials are refined by human activities using fossil fuels until the heat is dissipated and the materials are either released as wastes to the environment or recycled back into the system. From this diagram, one could argue that the most important activity of the economic process is the proper functioning of the hydrological cycle, since virtually all economic production and manufacturing are extremely water intensive. From the standpoint of a traditional economist, the hydrological cycle is not important because we pay next to nothing for it. A biophysical

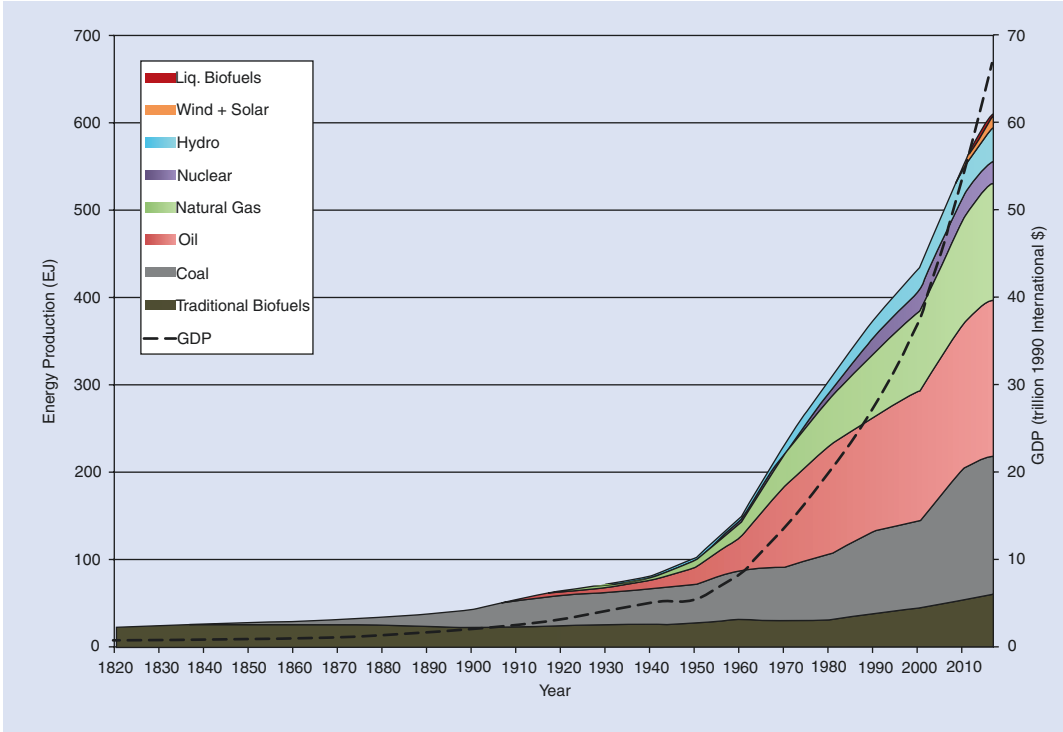

Fig. 4.1 Increase in fossil energy use and economic activity for the world

economist, on the other hand, would argue that it is critical for many reasons and that it is only because we can extract its services from nature at little direct monetary cost that we can have the high generation of wealth within today's economy.

A fundamental premise of biophysical economics is that wealth is produced basically by the application of energy, initially human muscles, draft animals or wood, and increasingly fossil fuels, to the resources of nature to generate wealth (Fig. 4.1). This can readily be seen from several pictures of agricultural harvesters (Figs. 4.2 and 4.3). Studies of the cost of energy to society show that energy has become much cheaper over past centuries as fossil fuels were exploited (Fig. 4.4).

4.3 Conceptual Sources of Biophysical Economics

Biophysical economics derives from three main sources of ideas: (1) earlier thinking by economists, such as François Quesnay and the eighteenth-century physiocrats, who called themselves "Les Economistes," and a few economists of the latter part of the nineteenth and the beginning of the twentieth centuries; (2) conceptual thinking about how ecosystems operate; and (3) scholars from various disciplines at the end of the twentieth century who introduced a new perspective about the limitation of the Earth to support an increasing human population. All of these ideas first came together under the word "biophysical" in a 1984 cover article by Cleveland et al. in *Science* entitled "A Biophysical Analysis of the United States Economy." These concepts gained a further following by the great interest in the "peak oil" movement of the first decade of the twenty-first century and a series of meetings on BioPhysical Economics in Syracuse, New York, starting in 2008. The participants formalized the International Society of BioPhysical Economics in 2015, and the organization continues to meet on an annual basis. These ideas are developed in more detail below.

Fig. 4.2 33 Horsepower combine in about 1900

Fig. 4.3 200 Horsepower combine in 2000

4.4 Biophysical Basis of Early Economists

The present social science focus of economics and economists was not particularly the case with earlier economists, who were more likely to ask "where does wealth come from?" than are most mainstream economists today. In general, these earlier economists started their economic analysis with the natural biophysical world, probably simply because they had common sense but also because they deemed inadequate the perspective of earlier mercantilists who had emphasized sources of wealth as "treasure" (e.g., precious metals) derived from mining or trade. The first formal school of economics, the French Physiocrats, focused on land as the basis for generating wealth [4]. The biophysical perspective continued with Thomas Malthus' famous "Essay on the Principle of Population," (there were six of them) which assumed that human populations would grow exponentially—because it seemed unlikely that anyone, other than the well-born, would control the "passion between the sexes"—unless somehow "checked" by factors that either reduced the birth rate or increased the death rate. Since Malthus had little faith in the "moral restraint" of the working classes and believed that birth control was "vice," he recommended a rather draconian social policy to increase the death rates among the poor. In Malthus'

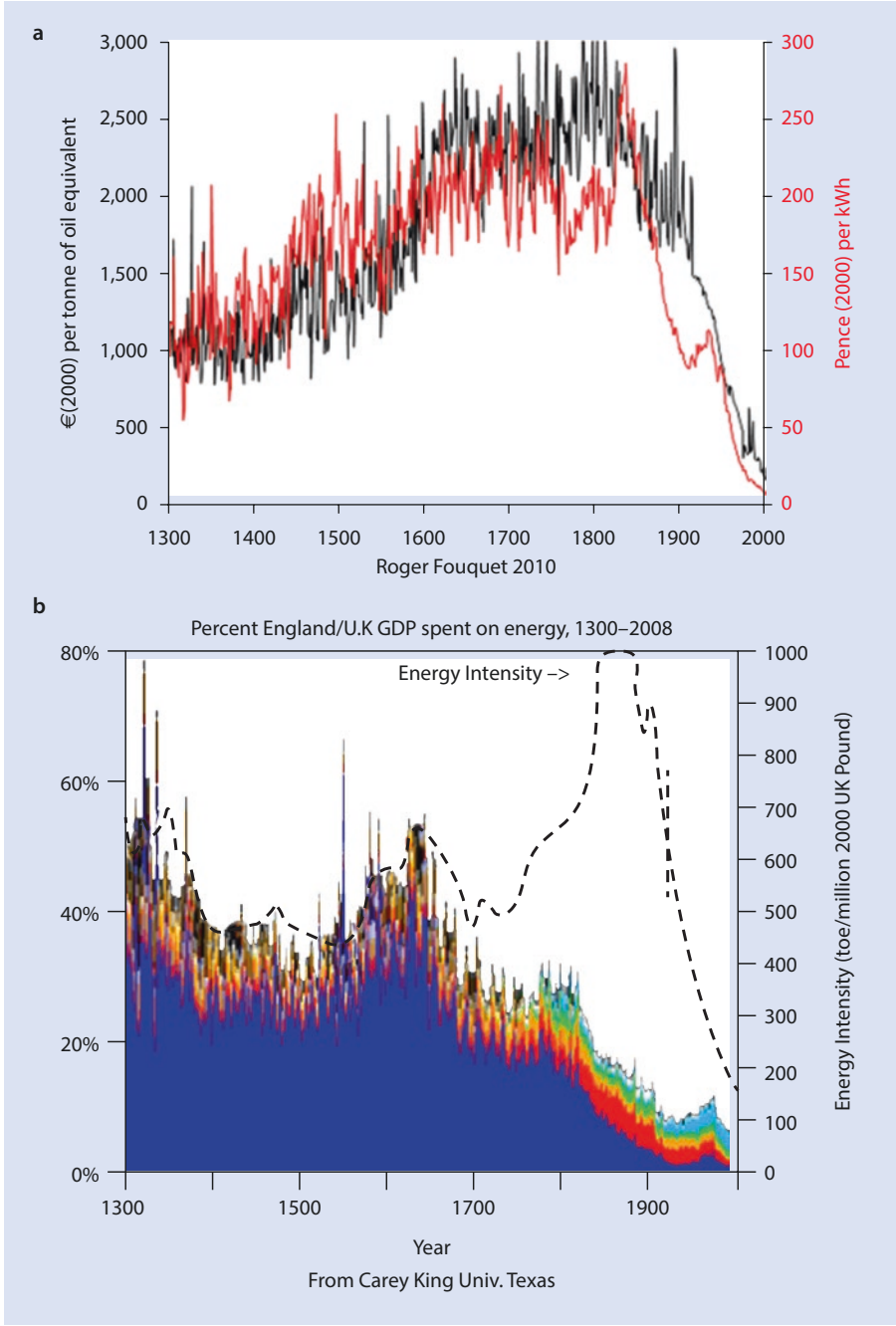

Fig. 4.4 **a** Efficiency of the global economy, as determined by the ratio of GDP produced to energy used (Source: Fouquet). **b** Percent of GDP spent on Energy for UK (From King)

view the agricultural production needed to feed this exponentially increasing human population could grow only linearly, i.e., less rapidly than the number of humans. He also opposed the importation of cheaper continental grains, as a limited food supply assured increasing rents for his patrons, the landed aristocracy, and squeezed the profits of the rival capitalists. It was this view that the human prospect was limited by inadequate food supplies and that class conflict was inevitable, which led the Victorian philosopher Thomas Carlisle to give economics the label of "the dismal science."

As chronicled in ▶ Chap. 2, Adam Smith and other classical economists focused on land

and especially labor as a means of expropriating the resources generated by the natural world, and then transforming them into materials that we perceive as constituting wealth. Later, David Ricardo made important observations about the general need to use land of increasingly inferior quality as populations (and hence total agricultural production) expanded. Karl Marx, who focused on the part played by labor in creating value, realized the crucial role played by nature in creating wealth. He was keenly interested in the long-term adverse effects of large-scale agriculture on soil quality and firmly believed that capitalism exploits the land as it does labor, and the process of capital accumulation creates a metabolic rift in the organic connection between humans and nature.

Thus a number of economists made important conceptual and philosophical advances that formed the basis upon which biophysical economics has been built. Early economists Quesnay, Malthus, Carlisle, Smith, Ricardo, and Marx all were aware of, to varying degrees, the importance of biophysical inputs and processes to the economy. Additionally, Kenneth Boulding in his paper "The Economics of Coming Spaceship Earth" focused on the impossibility of continued economic growth on a finite planet: "Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist." Nicholas Georgescu-Roegen was a Harvard-trained economist who found the intellectual structure of conventional neoclassical economics enormously misleading and wrote extensively detailing the failures of conventional economics. His most prominent contributions were *Energy and Economic Myths* and *The Entropy Law and the Economic Process.* But the real foundation for biophysical economics was laid by his student Herman Daly, who through a series of excellent books and presentations examined the biophysical requirements for modern economies. His main emphasis was that we could not grow indefinitely and that any growth at all would cause unacceptable damage to the Earth. His main vehicle for thinking about this was the development of "steady-state economics," that is, an economics not based on growth. In addition he was among the first, and certainly the most thoughtful, in criticizing the intellectual underpinnings of conventional economics because it did not begin with the biophysical reality of the physical systems that are essential for supplying the materials and energy required for any economic activity. Nor did it consider the limiting effects of entropy. Daly extended Karl Polanyi's idea of the embedded economy with a focus upon the economy as a subsystem of the planetary ecosystem. His thoughtful and gentle personality allowed him to deliver very sharp criticisms to the economic community from one of their own. Nevertheless, most of Daly's many followers came from outside, not inside, the discipline of economics. Other economists who made important contributions to biophysical economics include John Gowdy and Lisi Krall, especially as regards their work on humans as an ultrasocial species and the crucial role played by the production of surplus at the dawn of the Neolithic era.

4.5 Ecology as a Source of Ideas

Ecology as a concept for understanding nature dates back to at least Theophrastus in ancient Greece, and the economic importance of properly functioning natural systems was well recognized by various scientists in, for example, Ukraine and Russia during the first half of the twentieth century. But ecology as a self-understood academic discipline hardly existed before the middle of the last century. One key event was the publication of Eugene Odum's *Principles of Ecology*, and another was the publication of Howard Odum's (Eugene's younger brother) *Environment, Power, and Society*. The latter was an ambitious attempt to show commonalities among various natural ecosystems and human societies using energy flow diagrams. Thus we can consider ecosystems such as natural streams, forests, or grasslands as economic systems ([2, 5]; ◘ Fig. 4.5). These systems have "economic" structures for production (photosynthesis), consumption (grazing, predation, respiration), and transfer of "goods" (food, minerals) through exchange processes (e.g., transfer of materials and energy between the physical environment and organisms through processes of plant uptake of nutrients and capture of energy, plant and animal uptake of water, and transfer through food chains). They are different in that the human economy is the result of conscious effort by humans and their expenditure of energy to change nature into what humans want.

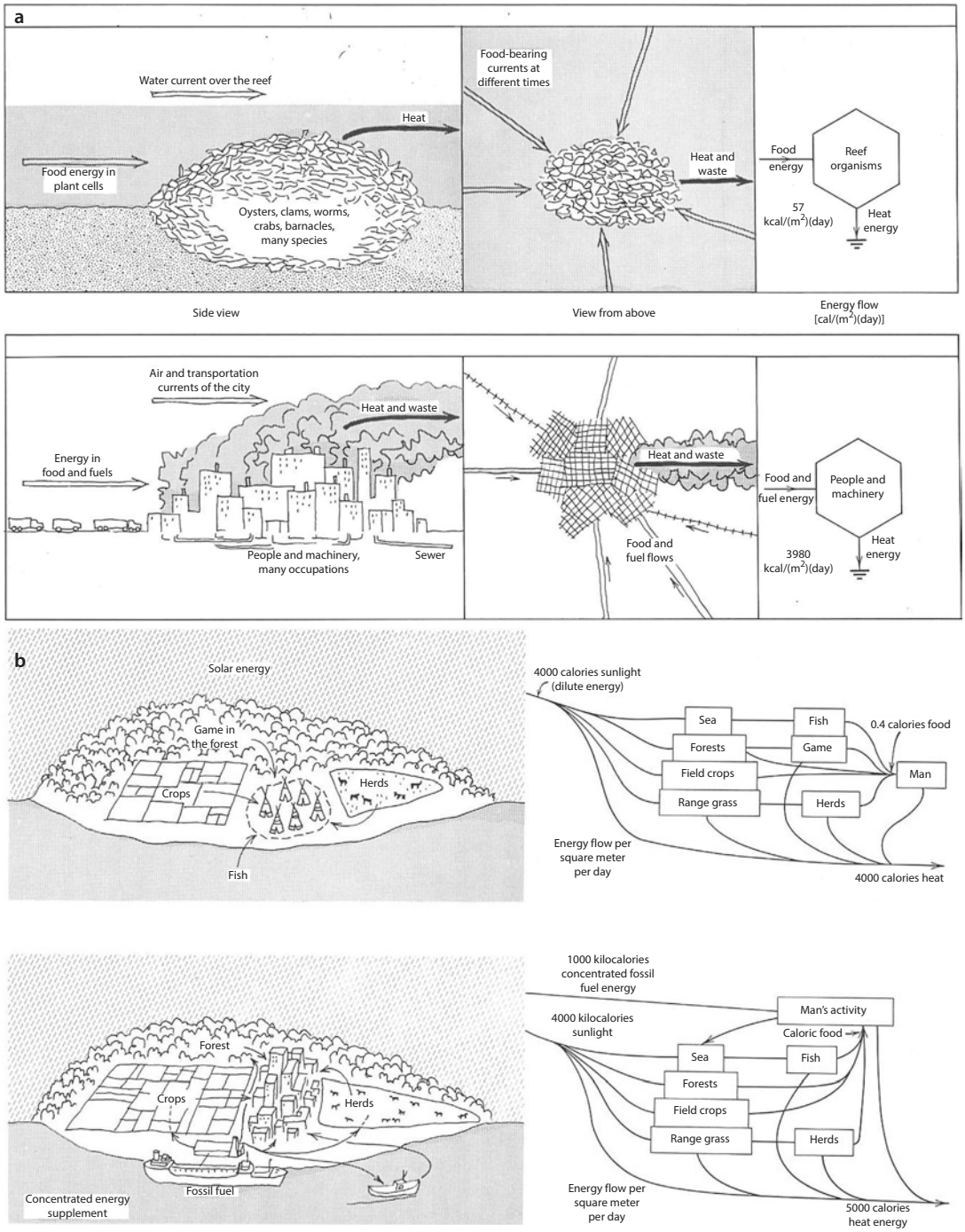

Fig. 4.5 **a** Similarities of oyster reef cities in nature and a human city (From Odum [2]). Both are necessarily subsidized by energies ging food in from elsewhere and removing wastes. **b** Comparison of agrarian system with industrial system (From Odum [2])

A critically important insight that has been gained from the study of these natural ecosystems is the importance of a thermodynamic perspective. While the importance of energy for biology was well recognized by, for example, Ludwig Boltzmann as early as 1880, energy as a concept was not well understood during the time period when modern economics was being developed.

Whether economics as a discipline would have been built on a foundation of thermodynamics, as were physics, chemistry, and ecology, if thermodynamics had been better developed during modern economics formative stages is impossible to answer but seems likely [6].

As thermodynamics was developed, ecologists began to understand that in the absence of a continual input of energy, the highly ordered molecules within an ecosystem will, over time, degrade into completely random assemblages. It is only the continual input of energy from the sun, the capture of this energy by green plants, and the effective transfer of energy to other components of the system that allows ecosystems and their components to fight the general tendency of all things toward randomness (often called a tendency for disorder or entropy to increase). Ecosystems have often been called "self-organized" entities; organisms within the ecosystem, and perhaps ecosystems themselves, interact to build a biological structure that best captures and utilizes available energy [7]. The blueprints laid down in an organism's DNA are fine-tuned through natural selection so that energy may be used to capture, reorder, and maintain both additional energy and the molecules in that organism in the otherwise extremely unlikely patterns that we call life. Energy is captured and used to generate biological structure, which in turn maintains, replicates, and sometimes changes itself through natural selection. It does not take too much imagination to transfer this concept to human economies, as both are equally biophysically based, although additionally powered by fossil fuels (◘ Fig. 4.5). This is what Howard Odum initiated in *Environment Power and Society* and other publications [8].

A particularly interesting and important concept developed for both natural and economic systems by Howard Odum was "the maximum power principle" (MPP). Odum and his colleague physicist Richard Pinkerton started with simple physical systems such as Atwood's machine (a simple pulley with two baskets that allowed differential loading of energy inputs and backforce [9]). They then change the ratio between the force (the weight in the heavier, descending basket) and the backforce (the weight of the load ("goods") in the ascending basket). They found that the maximum useful work that could be undertaken per unit of time (i.e., power) was when the heavier basket was twice the weight (gravitational force) of the ascending basket. If the baskets were more equal in weight, more "goods" could be delivered per trip and per unit input energy, but the machine worked more slowly even if more efficiently. Conversely, when the baskets were very different in weight, the goods were delivered very rapidly, but not much per trip, and most of the input energy went into heat as the basket hit the ground. The maximum useful work per unit time was when the ratio between the two weights, and hence forces, was 2:1. Odum and Pinkerton went on in that paper, and many more, with many other examples including economic analogies. The basic idea was that in a competitive world, one cannot be too efficient, for otherwise one's competitors would exploit resources before you were able to. The consequences are not always comfortable. For example, if the United States chose to use Middle Eastern oil more slowly, would that open up the resource for additional exploitation by the Chinese?

Most of us would not consider systems of nature as "real" economies because that term tends to be reserved for systems that include humans, human processes, market transactions, money, and/or other human-directed activities. Nevertheless, actual economies (including those of the city of Syracuse, NY, or of the country of Costa Rica) are, in fact, subject to the same forces and laws of thermodynamics as natural ecosystems and have much in common with them—structure, function, energy requirements, material cycles, and so on. In our view modern cities, agricultural systems, and even entire nations are indeed industrial ecosystems. Since the structure of many human-constructed systems (e.g., cities) contains so much more abiotic and animal mass than that of natural systems, the energy requirement to construct and maintain them is much larger and must be supplied from outside the system. Today this requires not only the usual input of solar energy but also the concentration of massive quantities of fossil fuels and energy-intensive materials, which in turn generate enormous "ecological footprints" on the rest of the world. Hence these "real" economies are as much about the movement of materials and the use and dissipation of energy as they are about the social or human-involved transactions.

As a consequence of studying natural systems from this perspective, many ecologists, led by Howard Odum [e.g. 2, 8], were quite ready to begin to look at economies from an energy and

material perspective, and they already had the conceptual, measurement, and modeling tools to do so. They found ready acceptance and collusion with Herman Daly and a very few other economists, but no interest at all from traditional neoclassical economists.

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4.6 Limits to Growth

The third main source of ideas that led to the development of biophysical economics was a series of quite startling and, many would say, pessimistic scientific reports about the future that took place in about 1970. The most important, or at least the ones that received the most attention, were the "Club of Rome's" *Limits to Growth* [10] and *The Population Bomb* [11] by Paul Ehrlich. *The Limits to Growth* was the result of a computer model generated at MIT, initially by Jay Forrester, and then refined and promulgated by his students Dennis Meadows, Donella Meadows, Jorgen Randers, and William Behrens III. The model was a very basic projection of human population, including birth rate and death rate, per capita industrial production, per capita food production, pollution, and nonrenewable resources, which is modeled as one entity that is depleted over time. The results of the "standard run" generated growth in population, food production, and industrial production for a while but eventually serious complications due to pollution or resource depletion that led to serious population decline. The investigators varied their assumptions in many ways to see if they could generate a scenario that was stable. Counterintuitively, increasing investments or controlling pollutants only delayed the negative impacts. In the model, it was only by extreme population control and eliminating *all* investments that a stable future could be derived. The model and its critics are discussed further in ▶ Chap. 12. *The Population Bomb* discussed the growing human populations and the many problems associated with humans using more and more of the Earth's resources to support them. This too predicted quite dire implications of the continuing population growth. While the most extreme of Ehrlich's predictions did not come true, there are many ways that in fact his predictions have come to pass [12].

These reports added concerns about human population growth and pollution to the existing concerns based on the predictions by Shell Oil Geologist M. King Hubbert [13] of the inability of both the United States and the world to keep increasing the production of petroleum. Hubbert assumed that over time the use of a nonrenewable resource would grow and then decline in approximately a normal-shaped (bell-shaped) curve, initially increasing rapidly and then reaching one (or several) peak when about half of the resource was consumed. Again, the results of this projection are somewhat ambiguous: oil is still abundant and relatively cheap (although more expensive than in the past), but globally conventional oil has ceased growing or nearly so. But a country-by-country analysis shows that oil production in most countries does follow fairly closely a Hubbert curve [14]. As we discuss later, the timing of some of these predictions for the globe may be a little off, while the fundamental pattern projected is very much on target.

These reports implied in various ways that the human population appeared to be becoming very large relative to the resource base needed to support them—especially at a relatively high level of affluence—and that it appeared that some rather severe "crashes" of populations and civilizations might be in store. Meanwhile, many new reports in scientific journals were published about the many environmental problems such as acid rain, global warming, pollution of many kinds, loss of biodiversity, and the depletion of the Earth's protective ozone layer. The oil shortages, the gasoline lines, and some electricity shortages in the 1970s and early 1980s all seemed to give credibility to the point of view that our population and our economy had in many ways exceeded the world's "carrying capacity" for humans, that is, the ability of the world to support humans and their increasingly affluent lifestyle.

Universities hired many new people in the previously obscure disciplines of ecology and environmental sciences, and there was a great surge of interest by students in issues related to resources and the environment. Although courses in environmental economics were added to some college catalogs, most economists ignored these issues or or, if anything, modeled nature as part of the economy and added in environmental factors to the list of things that would be regulated by rational individuals responding to price incentives. The notion of external limits to growth, based on biophysical constraints, got a chilly reception from the community of mainstream economists, although the

idea of an economy limited by nature began to develop following among political economists in the early 1970s [15] . Although economists have written about the *internal* limits to growth since the eighteenth century, these new works raised a new possibility: our futures would be limited by nature as well. Historically, humans have been able to transcend nature's limits by employing increasing amounts of energy to the problems at hand. But were we nearing those limits, either in supplies of energy or in the consequences of using it? If so, the age of convenience and growth of affluence and human well-being, primarily in the global North, [15] might be replaced by living within our means or even degrowth. The message was not popular. President Jimmy Carter discussed on television the need for Americans to conserve and even installed solar collectors on the White House roof. He said that the American people should view the energy crisis as "the moral equivalent of war." For many people, it did seem like humans had reached the limit of the abilities of the Earth to support our species.

Most economists, however, did not accept the absolute scarcity of resources or the concept of limits to growth. The return to growth, they said, was just a matter of implementing a series of proper incentives and market-based reforms, as well as dispensing with the dangerous ideas of absolute limits. A series of scathing reports appeared directed at those scientists who wrote articles with the "limit" perspective (e.g., Passell et al. [16]). They argued that economies had built-in market-related mechanisms that would deal with short-term (relative) scarcities. Technical innovations and resource substitutions, driven by market incentives, would solve the longer-term issues. Critics of the early antinuclear movement belittled the idea that using less electricity or generating it from less dangerous sources was remotely viable. For them it was generate more nuclear power or "freeze in the dark."

These three lines of thought converged more formally in mid-1985 with the development of the International Society for Ecological Economics, along with national affiliates, and the journal, *Ecological Economics*. There was a sense by many that this society and journal, while undertaking important research, focused too much on putting a dollar value on environmental goods and services while mostly missing the issues of depletion, the institutional context in which economic decision-making takes place [17], and a continued commitment to neoclassical models and analysis. Consequently about 20 years later, the International Society for Biophysical Economics was formed. Starting in 2016, the initiation of the journal *Biophysical Economics and Resource Quality* devoted itself to publishing papers exclusively grounded in biophysical economics. Some economists, increasingly, are agreeing with biophysical economists on the need to reform basic concepts in economics to reflect the importance of energy [e.g., 18].

4.7 What Can One Do with Biophysical Economics?

Biophysical economics thus far has focused on five major issues:

1. The inadequacy of neoclassical economics (see ▶ Chap. 3)
2. The need to incorporate biophysical realities into economics (see ▶ Chaps. 3, 4, and 5)
3. The importance of the fossil fuel revolution for economic growth (see ▶ Chaps. 4, 6, 7, 8, 9, 10, and 11)
4. Limits to growth as a real (if complex) issue (▶ Chap. 12)
   - This includes peak oil, declining energy returns on investment (EROI).
   - Can renewables substitute for fossil fuels?
5. The need to improve and generate better estimates for EROI and equations for biophysical economics (see ▶ Chap. 18)

Money is of great practical concern in day-to-day life as we get paid or exchange money and so gain access to food, fuel, or housing. In addition, many financial practices that seem closely related, such as accounting, bookkeeping, and simply balancing one's checkbook, are based on money and have great practical importance and apparent reality. In fact, those of us who advocate biophysical economics realize that money is useful as a medium of exchange. And of course there is no substitute for proper economic bookkeeping and the normal everyday use of money as a medium of exchange to obtain needed goods and services. But what about the theory behind economics? Is that the best way to understand the routine use of money in our economy? We think not, as is obvious. Others disagree. Conventional economics is

useful to those at the top, because it justifies the prevailing economic order. It treats continuing consumption of more and more stuff as the key to happiness and holds that a private enterprise economy is the best society that has ever existed. Most importantly conventional economics is based on money as the key to valuing and acquiring stuff. Thus even the most arcane economics has a certain appeal because it uses money, which translates easily in most people's mind.

But what is important to understand is that money in its modern form is fiat money or "money by decree." As such it has no intrinsic value but value only in representing the willingness of society or its representatives to accept it for payment. The government accepts the money for payment of taxes. We also use money to acquire energy or energy-derived products to generate the good or service that will then be made available to the bearer of the money. *Thus, money is a lien, meaning a legitimate claim, on energy (or energy that has been spent), as well as labor, commodities, or money itself.* As we saw in ▶ Chap. 1, money can serve as capital and as a medium for speculation as well. Money creation is how banks make profits, but ultimately money can be best understood as a lien on energy.

Let us give an example. One might buy a wonderful, high-quality bagel in New York City for a dollar (more with cream cheese and/or lox). Behind that dollar lies many biophysical activities each of which must occur. Natural gas must be used in Louisiana to make fertilizer, which is then barged up the Mississippi River to Nebraska where a tractor uses oil to spread the fertilizer on the land and plant the wheat seeds. Later a tractor uses more diesel to harvest the wheat, which is then shipped by railroad to New York and ground into flour. Electricity is used to mix the flour and boil the water it is cooked in. Energy is used to make the fertilizer plant, the barge, the tractor, the railroad, and so on. It is the physical expenditure of energy to do all the work necessary to generate the bagel that is necessary, and the dollar is how we keep track of that. Part of the dollar goes to pay for the energy used at each step, and part of it is used to pay for those who directed the work (i.e., labor and management). Energy is also needed to give meaning to the worker's paycheck or to the proceeds given to capitalists through their profits. Roughly 5 megajoules (one-seventh of a liter of oil) of energy was used to make that one bagel.

In addition to, or overlapping with, the list given above, we can ask how biophysical economics has been applied by its practitioners. The first, most general application is visualizing how the economy operates and understanding how energy is required at each step. This can be seen by studying ◘ Fig. 3.3 carefully. This leads to a number of nonobvious implications. For example, if one wishes to live within nature's biophysical limits, then people in the rich nations of the world need to think mindfully about the energy used and embodied in their day-to-day lives and act accordingly.

A second major application of biophysical economics is to evaluate realistically the potential for economic expansion in poorer countries. Most of the world is quite poor, and there are many efforts directed at improving the lot of the poor, some successful and some not so much. Overall there has been a considerable improvement in the lot of the poor in the past six decades, and in fact since at least 1820, when according to one study, 90% of people were then living in extreme poverty compared to only 10% now living in extreme poverty, mostly in the global South [15]. Some might consider with Roser's numbers rather optimistic as about a third of the Earth's human population live on less than two dollars a day. Where has this increased wealth come from? The principle cause has been the continuing industrial revolution, which used fossil fuels to replace animate power and, most importantly, increase food production (see ◘ Figs. 4.1, 4.2, and 4.3).

Nevertheless, there is a dominant viewpoint among many of our agencies responsible for financing development, such as the World Bank, that what is important is not spending money in the public sector but turning as much as possible of the financial workings of a country over to the private sector. It is commonly held that the private sector is more efficient than government. Empirical analysis of this question does not clearly show that to be the case and in fact often the reverse [19]. The extreme view of the concept that it is better to privatize functions commonly undertaken by governments is called the "Washington Consensus," and it was used to guide development in Latin America in recent decades, often with disastrous results [20]. Biophysical economics approach has been used to examine these often misguided policies and alternatives that may offer hope for the poor (e.g., [21]).

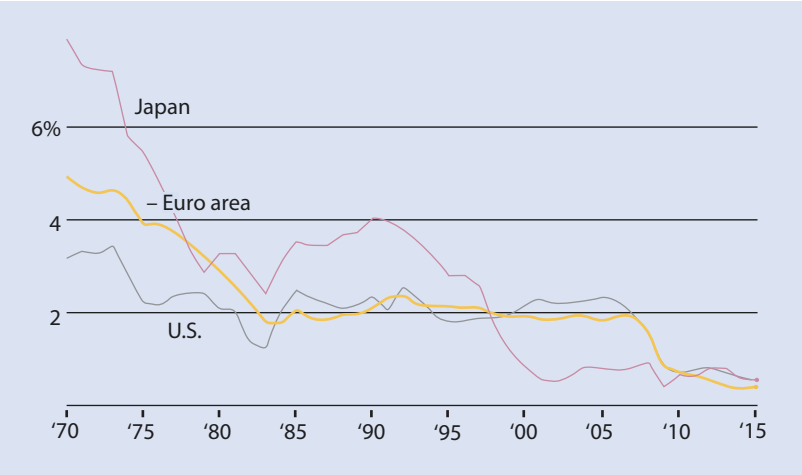

Fig. 4.6 Economic growth of Japan, Europe, and the United States, showing the general decline over time

A third application of biophysical economics is to understand some important trends in the world today and to help us prepare for a future that might be quite different. These trends include secular stagnation, peak oil and declining EROI. There are also a whole suite of issues around reducing carbon release and whether renewable energy can replace some important proportion of fossil fuels.

4.8 Secular Stagnation

The global North, from the end of Second World War until the 1970s, once Europe had recovered from the war, experienced historically unprecedented growth in energy use, and to some degree energy efficiency and economic output increased substantially (Fig. 4.1). But the growth rate of most of the world's industrialized economies has slowed since the 1970s. The economies of the United States, Europe, and Japan have experienced declining growth since the 1980s, and most of the current world economic growth is driven by China and India, although they too may be declining, (Fig. 4.6). As of mid-2017 the GDP of countries in Europe and Japan had been essentially stagnant for a decade or two. During the past decade, the United States had a GDP growth rate of about 1%, about half of the historical standard of 1.9% since the Civil War [22] and about the same as the population growth—hence there was no increase in average per capita wealth. Among economists there is considerable discussion and controversy about these essentially stagnant economies [e.g., 23]. Much of this focuses on factors internal to the economy: consumer spending, debt, banks, deficit spending, and Keynesianism—whether or why governmental deficit spending, which has been used extensively in the past to "jump start" economic growth, no longer works as it once did. We will discuss more extensively mainstream and heterodox views of secular stagnation in the next chapter.

Biophysical economics may provide such an explanation [24]. Most adherents to biophysical economics believe (as do many others) that conventional (neoclassical) economics is fundamentally flawed (see ▶ Chap. 3). Biophysical economics believes that there is a general relation between the declining abundance of resources, as reflected in lower production and EROI for oil and other important fuels, and the decline and cessation of growth (Fig. 4.7). Murphy and Hall put forth a model that gave a biophysical economics-based explanation of economic cycles that seems consistent with the actual behavior of economies(Fig. 4.8). The case for this was stronger up to mid-2015, when oil was trading at $100 a barrel. At the time of this writing, it is about $50 a barrel, still high by historical standards and relative to, e.g., the 1990s when growth was still strong. The OECD country with highest growth, although still low, is the United States. In the United States, natural gas, not quite as valuable as oil but still an excellent fuel for industry, was at a very low price, about a quarter of the long-term price, reflecting over production from fracked areas in, e.g., the Marcellus Shale in Pennsylvania. This could be the reason for the slightly higher growth of the

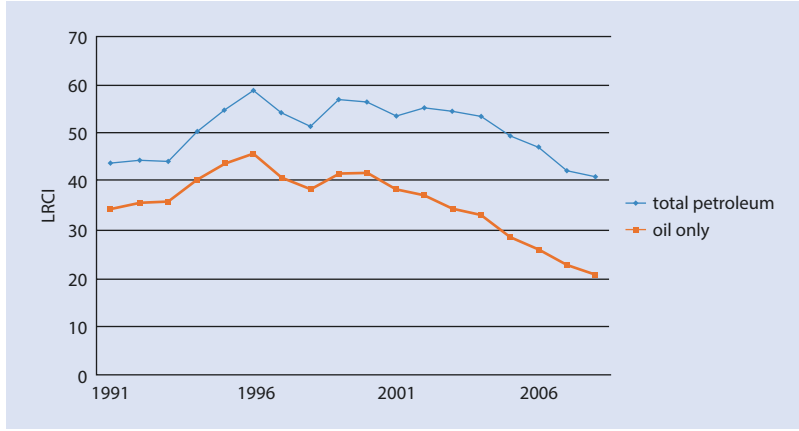

Fig. 4.7 Example of decline in EROI (Norwegian oil and gas; From [37])

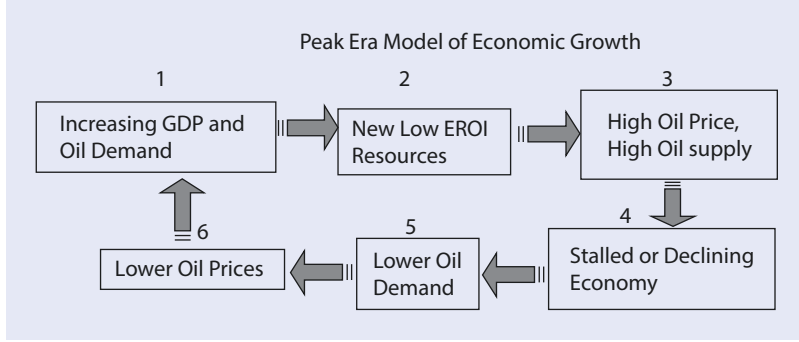

Fig. 4.8 Model of cycling of oil prices (From [38])

US economy compared to other OECD countries. Curiously the oil and gas companies are still drilling new wells even while they are losing money!

There may be another useful biophysical concept from ecology. Eugene Odum in 1969 wrote a good paper representing the behavior of ecosystems over successional time, that is, from the establishment or colonization of life at a site, such as an ecosystem that develops on a bare patch of land or a newly filled aquarium until the ecosystem reached "climax," when it no longer accumulates biomass. At first, as biomass became established, production (the capture of energy from sunlight) and respiration (the use of energy for maintenance metabolism by all living things) each increased rapidly, with photosynthesis being larger than respiration (Fig. 4.9). The difference between the two represented the energy absorbed by the increasing biomass. But then at some point, the respiration of the increasing biomass equaled the production of the plants, and the system stopped accumulating biomass. The relatively constant biomass remaining at steady state was limited by the respiration (i.e., for maintenance) energy costs being as large as the gain from the capture of energy from the incoming solar energy, and the system adapted to that. This takes place around the world as most ecosystems are limited by the incoming solar radiation (or water) and rather than growing indefinitely they reach a steady-state biomass level. Odum believed that human societies too would initially grow rapidly (i.e. new construction exceeding maintenance requirements, resulting in the accumulation of infrastructure) but then would approach equilibrium as energy costs to maintain infrastructure became very large. This is very different from the indefinite growth of economies expected by most economists. So have modern highly developed economies with enormous infrastructures (think roads and cities) reached a stage where all of the available energy is used for "maintenance metabolism" to support the infrastructure that exists and little is available for net growth? Could this be an explanation for secular stagnation? Will our existing growth-oriented economic models still be appropriate (Fig. 4.10)? Or is it sufficient to say that the growth of economies simply reflects the growth of the energy that allows that to happen, and that energy, once easy and cheap to get, is no

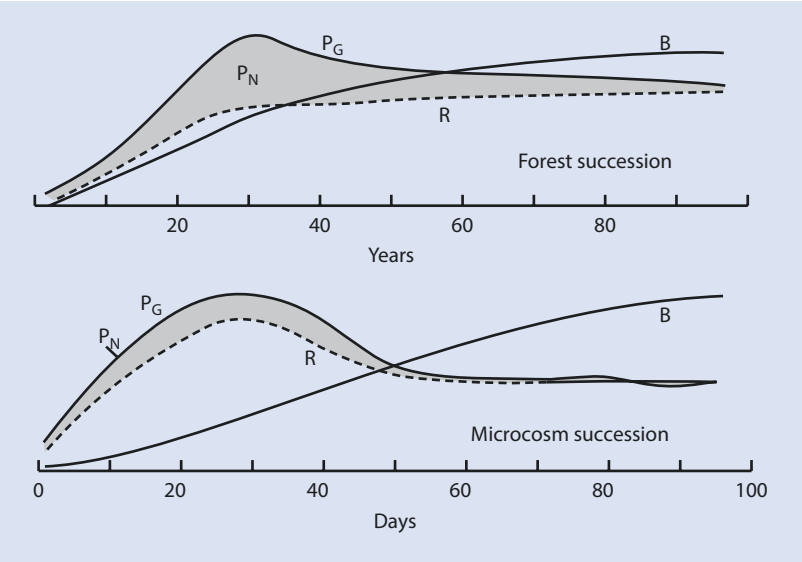

Fig. 4.9 Ecological concept of succession following disturbance (or initiation of ecosystem succession). As time passes in a novel ecosystem (such as in a new forest clearing), both photosynthesis and respiration increase, although initially photosynthesis increases more rapidly, resulting in the production of more biomass. Eventually the increasing biomass uses more and more energy for respiration, so photosynthesis and respiration are equal (called "climax") (From [39])

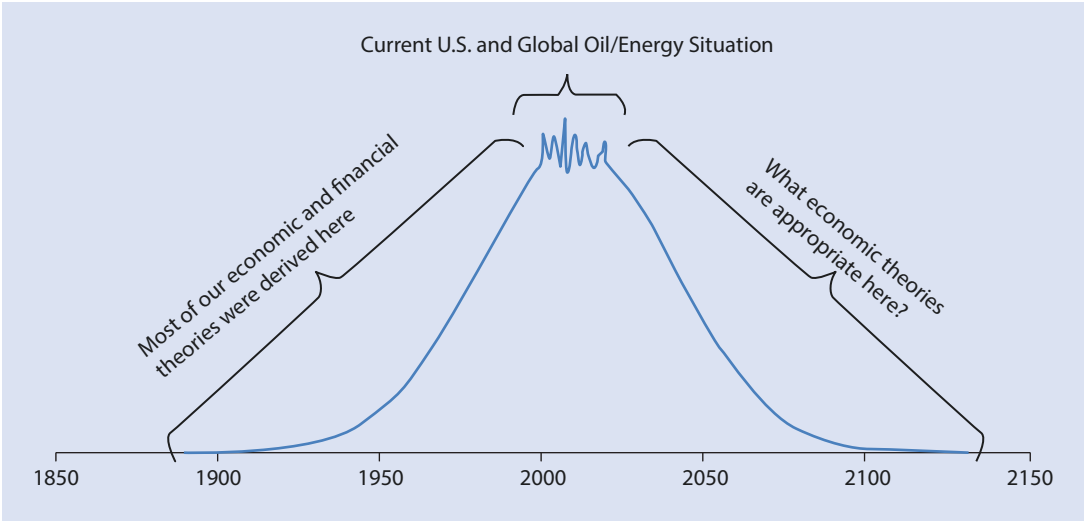

Fig. 4.10 Relation of our development of economic models relative to the general pattern of increase, stagnation, and eventual decline in production and availability of fossil fuels

longer so? Either way biophysical economics has approaches that appear very useful to understanding secular stagnation which should be explored much more than they have been so far.

Meanwhile, the main problem that we face with regard to fossil (and other) fuel supplies is not their total quantity on Earth (there are enormous supplies remaining) but their quality. To survive and thrive, all species must balance the relation between the energy cost of getting needed resources, including additional energy, and the energy (or other attributes) in the resource exploited. This applies to predators hunting for food who must compare the energy expended in the chase and the chances of success with the energy obtained from the prey. Likewise, human hunter-gatherer societies, if they are to survive, must generate substantial surpluses of energy relative to their own investment energies. It also applies to modern human industrial economies, although they are different in that the energy invested and gained is not metabolic but exosomatic (outside the body) energy. Thus, a critically important issue for examining our energy future

is what is called energy return on investment (EROI) of fuels. Investments are required to get fossil and other fuels out of the ground and into society. These investments are in terms of energy as well as dollars, and just as we need a profit from a financial investment, we need a net energy profit from our energy resources for society to continue. We will develop these concepts more fully later in ▶ Chaps. 18 and 19.

Perhaps the most important policy question for us now is how we should make our energy investments. Huge investments will be needed if we are to maintain the enormous human infrastructure that we have built—simply to fight the inevitable generation of entropy which nature dictates will occur. As we move into the future, EROI is a critically important component of the decisions we have to make but hardly sufficient by itself. The main problems that we face at this time with respect to understanding our situation are as follows:

1. The apparently incessant decline in EROI which will greatly limit our options for investing in new energy technologies, whatever they might be.
2. The need for professional, objective means of gathering the needed data and evaluating the alternative energy sources and claims. It would seem that such an evaluation would have to come from peer-reviewed or government-sponsored program.
3. The total inadequacy of conventional economics for the job.

4.9 Why Have Not Most Traditional Economists Paid More Attention to Biophysical Economics?

Economists have had to pay little attention to biophysical economics largely because there seems to be no crushing limits to growth as of yet. Perhaps the basic question is whether Malthus has been put to rest by the evolving technology of modern society. Most economists would answer "Yes, Malthusian concerns have been put to rest, mostly by continuing technological advancement." According to Bridge [25], "there is a post scarcity narrative – a postindustrial (market-generated) resource triumphalism – in which resource scarcity no longer poses a limiting factor to economic development… Neoliberal prescriptions for marketization and privatization have come to dominate nearly all areas of public policy over the last two decades."

But there have been at least three biophysical factors that seem to be at least as important: the opening of the Americas to immigration by the surplus Europeans, their virtual extinction of the Native American potential competitors there, and the industrialization of agriculture, which generated an enormous increase in food production and removed the stranglehold of land as a fixed factor of production, upon which Malthus' entire theory depended. A fourth factor might be considered technology by itself, although most technologies were associated with industrialization so that we might consider them as a force working together. With this increasing creation of economic surplus, economics, starting with Keynes, focused increasingly on consumption and became more and more intertwined with the social sciences. Simultaneously, concepts of economic production have focused increasingly on capital as an abstract but critical notion, while labor has been reconstituted as "human capital," and land has simply been omitted. Recently, in an attempt to give value to nature, ecological economists have christened biophysical stocks as "natural capital" that subsequently produce flows known as natural resources. But the continuing abundance of energy, food, and disposable income by at least a large part of the developed world has tended to relax any concerns that economists might have about resource limitations and hence the need for biophysical economics. An additional issue is that economics as a discipline tends to be "hermetic," meaning completely enclosed within itself.

Many economists argue that since energy costs are equivalent to only some 5% of GDP, then they are trivial in importance compared to the rest of the economy and that we need not be too concerned about future possible energy shortages. But what if this cheap energy declines in abundance, as seems inevitable to many of us? When energy and minerals increased to 12% of GDP in the oil-constrained and economically devastated decade of the 1970s, as is likely to occur again, perhaps soon, the economic consequences were enormously adverse. Hamilton [26] has found that whenever the cost of energy approaches 10% of GDP, a recession will occur. One can argue that if the present 5% of GDP energy cost is subtracted from the current economy, most of the other 95% of GDP will cease to exist. In other words, we are

extremely lucky that we must pay only the extraction costs, rather than the full-value production, value to society, or replacement costs that Mother Nature might charge if there were mechanisms for her to do so. The full price would have to include the costs of natural capital depreciation, including both the fuel itself and the nature destroyed by its extraction, shipping and use, as well as the military costs of assuring resource availability. These we are hardly paying at present. If and when we run out of luck, and these costs come due, as will likely be the case, economics will become a whole new ball game in which the focus will return to production and which will result in a new way of thinking about monetary and energy investments. Thus, there are good reasons to examine economies from a biophysical and energy perspective as well as from a social- and market-based perspective. This may be a difficult leap initially, but the shift in perspective should become obvious and desirable once the idea is broached.

4.10 Are We Becoming More Resource Efficient?

The material demands for societies continue to grow despite very little empirical data to support the popular idea that economies are becoming more efficient in turning resources into economic production. In fact, considerable empirical data suggests that many economies are becoming less efficient (see, e.g., 27–29) even while total consumption increases nearly everywhere. (One partial exception to this statement is seen in the US economy since 1980, where GDP appears to be increasing somewhat more rapidly than the increase in resource use—although about half of that supposed increase in efficiency is through the increased proportional use of higher-quality fuels such as primary electricity). An extremely important question becomes: is petroleum a transition element along the energy source road from slaves to draft animals to water power to coal to oil and gas to…something else? Or are liquid and gaseous petroleum a one shot, extremely concentrated, relatively environmentally benign, high energy return on investment (EROI) premium fuels that we will never see again at such a large scale? We suspect the latter. A second critical question to which we do not yet know the answer is "which will win the race between innovation/substitution and depletion." In the case of petroleum from the United States, Mother Nature seems to be winning, as the EROI has declined from at least 30 to 1 in 1970 to 18 to 1 in the late 1990s [30, 31]. When Cleveland made appropriate corrections for the fact that increasingly we are investing higher-quality energies (e.g., electricity) into producing oil over time, the "quality-corrected" EROI has declined much more sharply, to about 11 to 1 [32]. The EROI for our legacy giant oil fields continues to decline even as new oil becomes more difficult to find [33]. Likewise, the energy cost of getting a ton of pure copper in the United States has increased despite massive increases in technology because the best ores are long gone [31, 32].

Essentially no resources today can be viewed as truly sustainable at present rates of production, consumption, and growth because all are subsidized by cheap petroleum. "Sustainability" projects such as those of ecotourism and, indeed, the entire economy of "sustainable" places such as Costa Rica [20] are not sustainable at all due to their ever-increasing dependency on petroleum and the debt that implies. The assumptions of growth-oriented economists have resulted in enormous economic and energy investments in developing tens of thousands of expensive resorts in many lovely but otherwise poverty-stricken tropical areas that are based on the assumption that the people that live there can and should live indefinitely on the crumbs that fall off the tables of the industrial world's momentary wealth. As the supply of cheap petroleum is exhausted through the increased exploitation of the Earth's highest-quality and most accessible energy resources while demand for its products continues to grow, the world will likely be in for some very rough sledding ahead. We as a society must recognize the need for a more biophysically based economic system, which includes a focus on material things such as land, water, soil, food, timber, other fibers, and, most importantly, energy. The economy must focus once again on the most fundamental issues of providing food, clothing, shelter, basic transportation, and other necessities. It must come up with real solutions to the critical problems we face (e.g., energy depletion and impacts, soil erosion, over fishing, water management, massive inequity in the distribution of wealth, etc.) that have been neglected thus far due to our temporary patch-up "solutions" of cheap oil. We must rethink very carefully what any increase in efficiency might bring because of Jevons'

paradox, for example [33]. We must think about the critically needed international development assistance in entirely new ways, and we cannot allow an unjustified faith in the supposed virtues of neoclassical economics mask where it is used to sanctify the massive neocolonialism sweeping the less developed world [34]. If in fact the grim results of the *Limits to Growth* do come to pass, do we castigate those politicians who for "moral" reasons removed population from the agenda of the US Government? How about those economists who argued foolishly against that model's utility or, more generally, a biophysical approach to the Earth's problems? Do we put them in jail for the lives lost and for encouraging us to make investments in the wrong places?

4.11 Biophysical Economics as a Means of Synthesizing Traditional Approaches to the Generation of Wealth

One can summarize the three most important approaches to economics as the physiocrats (with their focus on land), classical economics (with its focus on labor), and neoclassical economics (with its focus on capital). These seem to be completely independent conceptual approaches to economics. Yet all can be understood from a biophysical perspective as an appropriate focus on the main energy sources of their time. Land was important when the main energy input to economies was the sun: farmers redirected the solar energy of ecosystems to human and draft animal mouths, and wood provided the most important source of heat so that land became a source of wealth as emphasized by the physiocrats. During the late eighteenth and nineteenth century, workers were increasingly concentrated in factories where their physical efforts were important to the productive process. Over time, the landed gentry who owned large solar-collecting estates were replaced at the top of the financial and social ladder by the new mill owners and then industrialists who directed new production systems using the more concentrated energies of coal and then oil. Therefore, the physiocrats, such as Quesnay, were correct for the time and place in which they lived, when the land-derived capture of solar energy generated the most wealth. Adam Smith, a contemporary of Quesnay but living in England, was correct for the time and place in which he lived, when craft labor was increasingly the main way to generate wealth. Ninety years later, when artisans were replaced by unskilled factory operatives, and landed aristocrats were displaced by industrial capitalists, Marx was able to contribute penetrating insights into the relations of the new classes of people who controlled different types and quantities of energy flow. Perhaps today neoclassical economists are partially correct to put the focus on capital—which is the means of utilizing fossil energy. Unfortunately, when all inputs are considered capital, it is more difficult to see this than in the days when capital primarily signified means of production.

What these "mainstream" production functions fail to emphasize is what every biophysical economist knows to be the truth: it is the energy that does the work of producing wealth and is essential for its distribution as well, whether that energy is derived from land, labor, or capital-assisted fossil fuels. Ayres and Voudouris [35], Kummel [36], and Hall and Ko [29] have shown that the production of wealth in industrial societies is almost perfectly a linear function of the energy use in those societies and that the correlation gets tighter and tighter when proper corrections are made for the quality of the energy used (e.g., coal vs. electricity) and for the amount of energy actually applied to the process (e.g., electric arc vs. Bessemer furnaces). Much, perhaps most, technology is ultimately about these things. It may seem obvious now that wealth is generated by the application of energy by human society to the exploitation of natural resources. Nature generates the raw materials with solar and geological energies, and human-directed "work processes" are used to bring those materials into the economy as goods and services. These processes have been made enormously more powerful over time through technologies that are mostly ways to use more or higher-quality energies to do the job. Energy would be the first element to be considered by most natural scientists if they were asked to construct a production function because they are trained to think that way and because it is statistically the most important factor—more important empirically than either capital or labor [36]. Where neoclassical economics treats production as just another case of the maximization of individual preferences, biophysical economics treats production as scientists treat work—the transformation of inputs into outputs using energy while subject to the laws of thermodynamics.

4.12 Summary

Our expectations for our lives for the past several hundred years have been based on an expanding universe of lands (e.g., the Americas), energy, and energy returns on energy invested. This has generated in the minds of most of the world's affluent people the expectation that there was at least the possibility of their bettering their own material lot, and for many this indeed occurred. We hear it in the pronouncements of economists from all sides, how we are facing a situation where many young people no longer have an expectation of more than their parents. In fact, the issue often enters the political arena as a failure of this or that government to make the economy grow and some other governmental philosophy having some magic power to reinstate the growth that they perceived as normal, as a birthright. To some degree this decline in economic growth for average people is clearly because the reins of power have increasingly passed into the hands of the wealthy, who tend to look out for their own. Most of us no longer live in a democracy but rather a plutocracy, meaning the rule of the wealthy. But something else is happening too: Malthus is finally catching up with us, if not exactly now (it probably is) then it is likely to come on in spades soon. The global population and its affluence can no longer be supported without piling up enormous debt, in monetary terms but also energetically and environmentally. Everywhere we look there are serious environmental issues starting with the potential impacts of climate change. There is certainly a lot of attention paid in some circles to climate change. But we believe the potential impact on our future society from issues related to energy supply and EROI are likely to be as large or even larger. It is likely that the effects of both will occur in the same time frame, probably the next few generations or perhaps sooner. Hopefully the understanding and use of EROI in analyses and public media will help soften the hard landing ahead of us, as the high-quality fossil fuels that have allowed many of the world's 7.3 billion people to live in relative luxury by the standards of old are increasingly depleted.

But neither our economists nor our politicians have the conceptual base or mental models to deal with this and still rely on mental models where the only operational levers for society are within the economy and are often some kind of untested political ideology. Rather economists must understand that much of what has determined human history and is likely to continue to do so comes from outside the immediate economy and is far less susceptible to internal manipulation (◘ Fig. 3.3). Biophysical economics is one antidote to this but hardly sufficient. We need an entirely new approach to education, including how we can work together to face a world with increased constraints on our energy and economic growth (◘ Fig. 4.10). Our present economic conceptual and mathematical models are not only inappropriate but hugely misleading if and as we enter this future.

Additional appropriate references can be found at a supplement to our paper "Hydrocarbons and the Evolution of human culture" (Nature 426 no. 6964. p. 318–322). ► www.nature.com/nature/journal/v426/n6964/extref/nature02130-s1.doc

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