The Need for, and the Growing Importance of, BioPhysical Economics

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Abstract:

Actual economies are based upon a variety of processes whereby humans interact with nature: Extraction; production; distribution; consumption; and waste production. Material goods and energy-requiring services originate not in markets but in the Earth. But for the past 150 years, economics has been treated primarily as a social science. The conceptual model upon which mainstream (neoclassical) economics bases its analyses consist of a circular flow of income between producers and consumers, mediated by means of markets. In this "perpetual motion" of interactions between firms that produce and households that consume, little or no accounting is given to the flow of energy and materials from the environment and back again, and little account given to human interactions that take place outside of market processes. Analyses by natural scientists (and others) find that the conventional model is simply not credible. In this paper we bring to the attention of the readership of this new journal the approach of BioPhysical Economics, an important but not widely understood development in economic theory. We review these criticisms and offer the basic concepts to construct a completely new approach to economics, one that will probably be essential in our future that is likely to be highly constrained by climatic, other environmental, resource depletion and other BioPhysical issues.

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INTRODUCTION

We wish to bring to the attention of the readership of this important new journal a critical but not widely understood development in economic theory that is yet to be well covered in the traditional economic or financial outlets. The development focuses on the need to moor economics within the natural sciences and within the natural world within which it must exist. This is our main point, which we develop down a few paragraphs, but first we must align our critiques with those coming from the perspective of more traditional economics.

Many, perhaps most, economists are aware of various deficiencies of conventional (neoclassical) economics (NCE) and the many criticisms that have been leveled at the conventional model by notable mainstream economists, even while most reject or at least ignore these criticisms. The criticisms have come from respected neoclassical economists, such as Thomas Piketty and even Nobel Prize winners such as Paul Krugman and Joseph Stiglitz. Together these and other economists have provided critiques of some of the most fundamental aspects of the neoclassical point of view. Krugman, who won his Nobel Prize for introducing increasing returns to scale into orthodox trade theory, generates a Keynesian critique of neoclassical economics, and especially the theory of “efficient markets”. He has embraced the existence of long-term slow growth, or secular stagnation, and regularly points out the disparities in income distribution and the losses in efficiency that occur due to a skewing of income and wealth towards the very wealthy. Krugman recommends traditional Keynesian measures of income support and government infrastructure spending to renew economic growth (e.g. Krugman 2013). Income inequality is also a dominant theme in the work of Nobel Laureate Stiglitz, who received the Nobel Prize for his work on asymmetric information. He made his mark on the popular imagination in 2002 with the publication of *Globalization and Its Discontents*, which drew attention to the perils of international speculative finance and unregulated movements of money capital across

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borders. In recent years he, like Krugman, has turned his attention to the problem of income inequality resulting from NCE. Stiglitz attributes much of the problem to the rise of rent seeking, or the searching out of unearned income by the corporate elites. He argues that we pay a high price for inequality in the form of reduced efficiency, productivity, and economic growth. Rent-seeking behavior is enabled by government policies that include tax cuts at the top, deregulation, and a decline in spending for education, technology and infrastructure. Since the 1980s productivity has grown six times faster than wages, and the rewards have been captured by those at the top of the income distribution. He calls for a large-scale liberal economic reform agenda that includes curbing the financial sector, stronger and more enforced competition laws, the end of corporate welfare, such as subsidies buried in the tax code, and the ending of subsidies for those who pass environmental cost of their industrial models onto humanity as a whole. Stiglitz believes that such a plan would allow markets to work as they should and restore democracy as well (Stiglitz 2013).

Piketty has also turned his attention to a critique of unequally distributed income and wealth. He argues that if the rate of return on wealth (r), exceeds the rate of economic growth (g) ($r > g$) income will flow towards wealth and capital. Rather than just being the result of bad policy, the trend towards wealth inequality is built into the dynamics of the economic system itself. Piketty also argues that two bulwarks of neoclassical theory, that the competitive economy generates full employment automatically, and that factors of production (workers and capitalists) are paid according to their marginal products (their individual contribution to output), have no bearing in the actual economy of today. The concentration of income at the top of the income distribution cannot be explained by differences in education and skill levels. As a matter of policy, Piketty calls for a massive tax on wealth, although he also calls this a useful utopia (Piketty 2014, Foster and Yates 2014).

Thus, these authors view NCE as an approach that tends to accumulate income and wealth disproportionately into the hands of those who already have it, while endorsing or avoiding consideration of what that means socially. Their criticisms have also included the over mathematization of an approach that led to the massive (and massively missed) economic collapse of 2008 because, in the words of Krugman, "Economists mistook beauty for truth". The beauty that Krugman spoke of was in the elegance of the equations, rather than in a deep understanding of how real economies work. Consequently, Piketty, Stiglitz and Krugman focus strongly upon the relation of slowing economic growth and the social consequences of growing income inequality. Their insights are crucial to the understanding of the economy from a social perspective, and their work is important to our arguments as a critique from within mainstream neoclassical theory.

Much More Fundamental Criticisms

While some neoclassical practitioners are aware of these critiques, few are aware of the much more basic criticism of the logical essence of economics by investigators from the natural sciences. Fewer still are knowledgeable of the rich contrarian literature found in institutional economics and heterodox political economy. These criticisms go far beyond the adverse societal consequences of neoclassical economics discussed so far. Rather these "new" criticisms upon which we focus are aimed at the logical basis of the discipline, its residency within social sciences, and the misrepresentation of the real biophysical underpinnings of actual economies. In the parlance of engineering: "The problems with economics are mostly from mis-specified relations". These criticisms were initiated mostly from within the ranks of natural scientists, who tend to find that the basic model does not meet the requirements of consistency with real physical systems, which it must. In addition, they often find the assumptions of the economic model to be rather unrealistic, not derived from formulating and testing hypotheses, or even foolish. They continue and build upon earlier criticisms leveled by economists themselves, including especially Nicholas Georgescu-Roegen (1975), Kenneth Boulding (1961) and Nobel Laureate in economics Wassily Leontief (1982). Leontief stated in the important journal Science that many economic models are unable "to advance, in any perceptible way, a systematic understanding of the structure and the operations of a real economic system". Instead, they are based on "sets of plausible but entirely arbitrary assumptions" leading to "precisely stated but irrelevant theoretical conclusions". He asked: "How long will researchers working in adjoining fields ... abstain from expressing serious concern about the splendid isolation within which academic economics now finds itself?" Thirty years later we ask that question again and attempt to answer it. Most fundamentally, those trained in the natural sciences look at the assumptions and procedures of conventional economics with something bordering on disbelief. How can so many distinguished scholars get away with such spurious, even specious, assumptions and still call it a "science", albeit a social science?

Let's start with some basic questions. What is it about economics that most individuals care? It is about, mostly, practical matters such as providing consumers with real physical entities: a roof over their heads, food on the table, perhaps a car in the garage, medical and educational services. These are real material goods and energy-requiring services. As such they must lie within the realm of the physical and biological world. However, neoclassical economists mostly ignore all the material actions that are the basis for the existence of these goods and services and care only about a far more abstract world. NCE rarely asks about the physical nature or origin of the goods and services, but only how they are distributed, or more specifically how does a consumer satisfy his or her assumedly "infinite" wants constrained by a finite budget, from a market place of near-infinite products. Earlier, pre-neoclassical economists often asked instead: "what are the origins of wealth and income, and how should they be distributed?" This led them inevitably to an examination of the material world. Contemporary mainstream economists, except for the aforementioned critics and others of their persuasion, rarely consider these questions in depth or at all.

The Special Role of Energy

The criticisms of economics as a discipline by natural scientists tend to focus on the fact that conventional (i.e. neoclassical) economics does not qualify as real science because (among many other things) its basic tenets and models: 1) break the laws of thermodynamics and conservation of materials, 2) uses inappropriate boundaries for its analysis and 3) presents its basic tenets as logical givens, or maintained hypotheses, not testable/tested hypotheses (see Mirowski 1989; Hall et al. 2001; Ayres and Warr 2005 and many other publications). If a freshman put the concept of NCE forth in a class in the natural sciences, it would not pass the most basic requirements for consistency with reality or with the most fundamental laws of nature (although it might get an A for creativity). This clearly limits the effectiveness by which mainstream economists can analyze many contemporary issues let alone the crucial questions for tomorrow, such as depletion, climate change and biodiversity loss, which depend upon an understanding of thermodynamics.

We call for an integration of economics with natural science. Why should economics be (only) a social science when it is basically about stuff and physical services? Are neoclassical economists social scientists, or scientists at all, when they sometimes see themselves as distinct from, and superior to, other social scientists? Why should economists be allowed to disregard the fundamental laws of nature and procedures of natural science when all other scientists know that if they did that they would be drummed out of their disciplinary club? This sleight of hand was accomplished in the years following the 1870s, when the focus of political economy changed from the idea that value was produced by the transformation of the materials of nature into exchangeable commodities using human labor, to that of value as the production of psychological, and unmeasurable, human utilities. William Stanley Jevons (1957) stated in about 1871 that economics was now simply the mechanics of utility and self-interest. By the 1890s nature was essentially omitted and even production was placed on a marginal utility basis, where it remains today within the mainstream, neoclassical, tradition and its derivatives. This basic proposition, that individuals are paid at the rate of their marginal products, is the point at which Krugman, Piketty and Stiglitz begin their dissent from the neoclassical income distribution theory.

The basic break with the laws that govern reality usually begins in chapter one of essentially any conventional economics textbook. For a model of how economies operate the students are usually given something like Fig. (**1**), where firms and households exchange money for goods and services or land, labor and capital. This of course is a misleading caricature of how real economies operate, which is captured in its essence in Fig. (**2**). This latter model not only reflects reality, it does not break laws of thermodynamics or conservation of materials -- as does Fig (**1**). This model also accounts for the enormous increase in affluence that occurred in the global North from 1750 forward, and especially in the twentieth century. This is done if one considers economic production a work process, requiring energy, which indeed it is. Economies undertake work at each step of Fig. (**2**), to extract fuels and materials from the Earth, concentrate and refine them and fashion them into the goods and services that we require and/or enjoy. As such, the increase in economic production (i.e. GDP) is highly correlated with the increase in our use of fossil fuels and other energy resources (Fig. **3**).

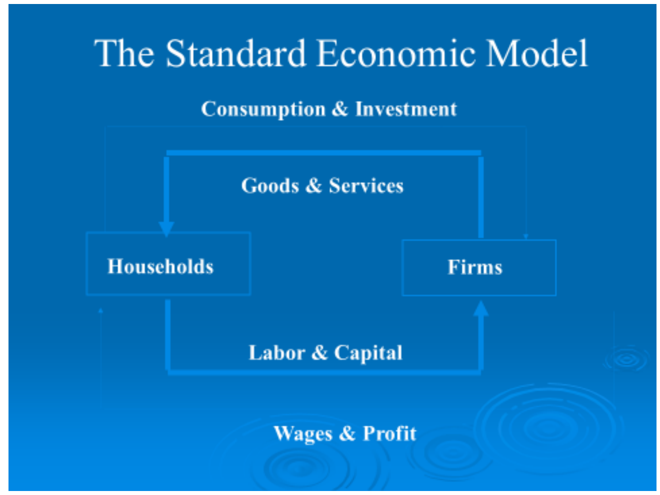

Fig. (1). The usual model of the economy found in most introductory economics textbooks, and generally used as a conceptual model in further studies. In this model, which is consistent neither with the laws of thermodynamics nor the conservation of matter, labor and capital flow from households to firms , and finished products from firms to households. Money flows in reverse.

To give a simple example of how important fossil energy is for our economic processes, one very strong human operates at about 100 Watts, so in a 10-hour day can do about a Kilowatt hour (KWh) of work, say lifting water up to our attic to charge our water supplies. For this we would pay him or her about $80 at minimum wage. Or we could get a KWh of work from an electric pump, and for this we would pay less than 12 cents, depending upon one's location, or 0.0015 as much. Thus, the availability of fossil fuels and the technologies to use them has meant an enormous increase in labor productivity, that is, the work a worker can do in a specific time period, for example, output per hour. We hardly think about having to "hew our wood and haul our water" anymore because they are done easily, cheaply and silently by fossil fuels. In our great grandparents' time such essential activities (including food production) took up most of a person's time, as they still do in many parts of Africa, Asia, and Latin America, and sometimes even in rural areas of the United States. The relation between energy and the long-term evolution of human society has been developed in many publications (including Hall et al. 2003, King et al. 2015 and Hall and Klitgaard 2017). Of particular importance is that neoclassical economics gives low value to energy because of its low price, normally only 5-10 percent of GDP. But energy is critically important to economies *because* of its low price, and because we can do so much work on so little money!

Energy Availability

Hence energy availability is a critical issue in economics, both in terms of understanding the past and the present but also in

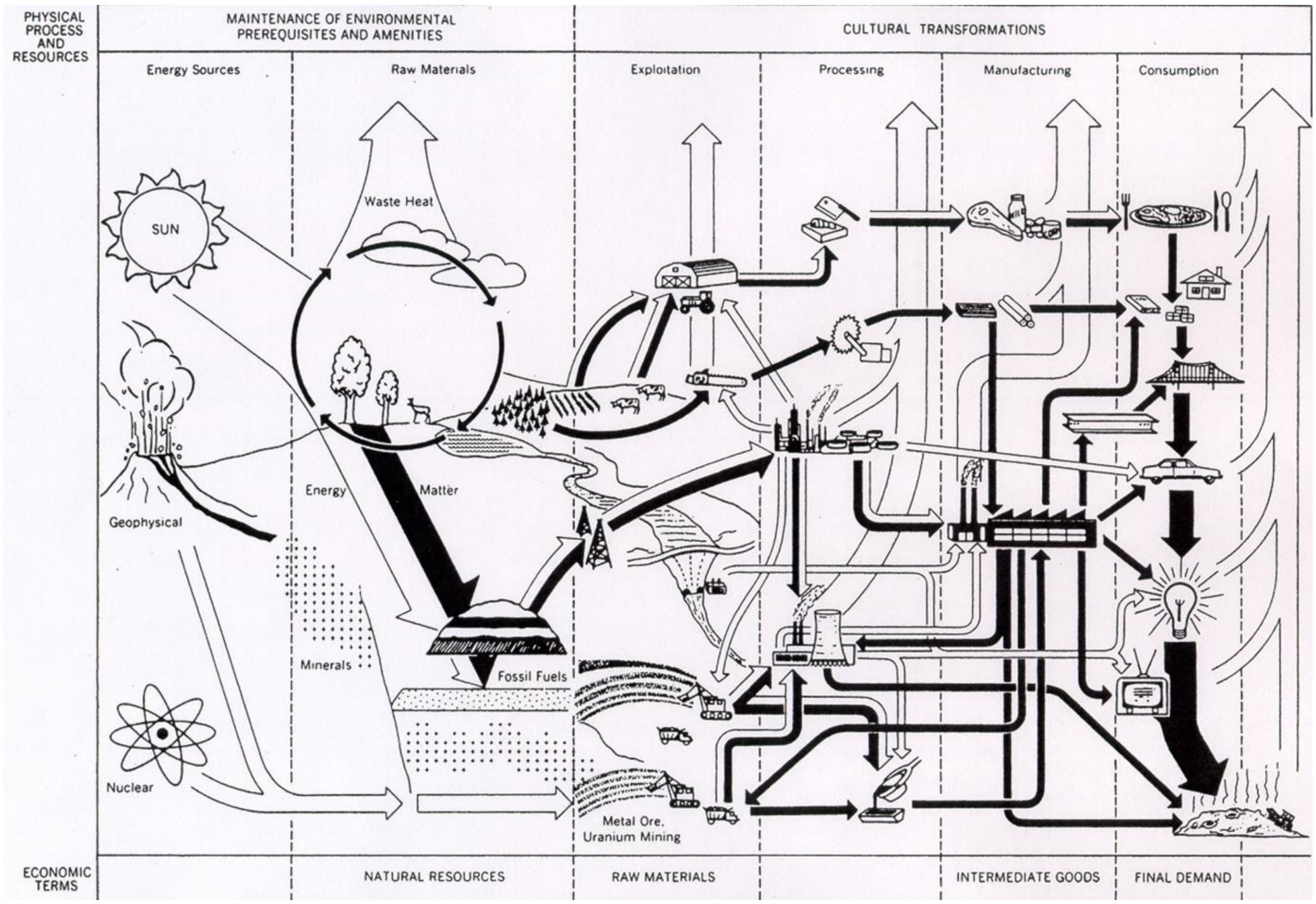

Fig. (2). Our perception of the simplest diagram that one could use to represent a real economy, which is nevertheless far more complex and infinitely more accurate than (Fig. **1**). This diagram, and real economies, includes (from left to right): (1) energy sources (principally, the sun) that are essential for any economy; (2) the material that circulates upon the earth's surface through natural and semi-natural ecosystems; and (3) the human-dominated steps of exploitation, processing, manufacturing and consumption. Black and white 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.

terms of predicting, or perhaps more realistically, guessing more intelligently, the future. There are two critical aspects of energy availability: first, the ability of humans to wrest energy from the Earth and second, the energy (and hence financial) cost of obtaining that energy. With respect to the first issue there are two prevailing views: The mainstream view holds that if money is available, energy will be forthcoming. In other words that market dynamics will insure the quantity of energy supplies indefinitely. The countervailing view, held by, for example, many geologists, is that the Earth has finite energy supplies, and that as time passes energy resources, like all other mined materials, will be depleted. The most famous manifestation of this is the "Hubbert Curve" initially derived by Shell oil geologist Marion King Hubbert in 1955. He said that the finding and hence the later production of oil would follow a rough normal or bell-shaped curve over time, first growing slowly, then exponentially, then slowing to a peak when approximately half the extractable resource had been exploited, then declining slowly until discovery, and hence production, reached or approached zero. For Hubbert the issue was not "when will we run out of oil" but rather "when can we no longer count on the production of oil to continue to increase year after year". This perspective was ultimately reinforced by reality, for that is what conventional oil production has done for almost all oil-producing countries except some of the largest (see e.g. Brandt 2007; Nawashi *et al.* 2010; Hallock *et al.* 2014). According to geologist Colin Campbell we have entered the "Second half of the age of oil", where oil production no longer increases and will soon start declining.

Many economists did not like the Hubbert prediction at all, because it negated the perspective of human control over nature. Adelman and Lynch (e.g. 1997) predicted that if indeed there were a dropping of oil production then this would act as a financial incentive for oil companies to find more oil, perhaps by increasing the technology used to find and produce the oil. Hubbert famously predicted in 1955 that oil production in the United States would peak in 1970, which it did. U.S. Oil production dropped steadily year after year from 1970 until 2007, when the new technologies of horizontal drilling and hydraulic fracturing generated a renaissance of oil production up to a new peak in 2019. Many energy analysts argue that while the new technologies are in fact generating more oil they are doing so at a financial loss to companies even at relatively high prices of $75 to $100 per barrel (let alone the $50 at the time of this writing) and that oil companies will soon exhaust the "sweet spots" available—indeed that the fracking business

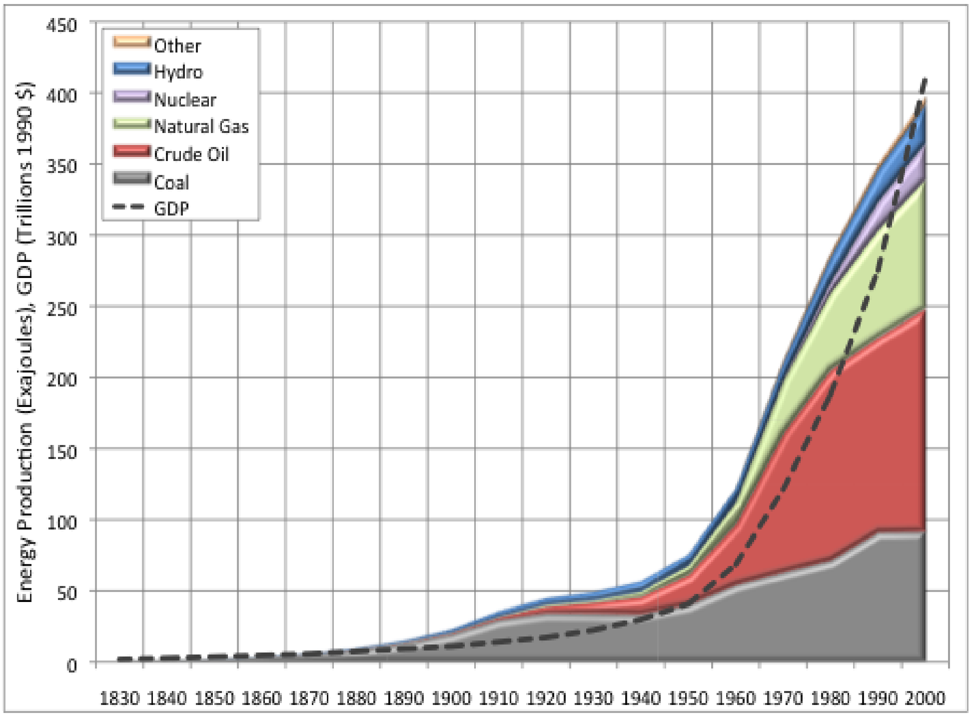

Fig. (3). Pattern of increase in the use of fossil fuels globally over the past roughly two centuries, with the increase in inflation-corrected global GDP, which obviously has a similar pattern.

is an enormous Ponzi scheme by which profits on earlier investments are derived only from subsequent investments -- e.g. Berman (2016). At the same time the production of "conventional" oil globaly seems to have reached an "undulating plateau" since 2005. Predictions for the medium term are a continued modest increase in demand year over year and a clear peak in oil (and "all liquids" which includes e.g. natural gas liquids and biofuels) and even production of all fossil fuels by 2025 to 2050, followed by a sharp decline (Mohr et al. 2015). Such a decline would be followed by enormous and quite varied impacts on society's economies, even if there was an unprecedented and quite unlikely increase in solar power far beyond anything we have done yet.

The second concern about energy availability centers around the concept of the quality of energy. Oil deposits in the ground are not at all homogenous but vary in many different respects: the degree to which the oil has been "cooked" (or, chemically speaking, reduced) and concentrated, the location, depth and size of the deposit, whether it is onshore or offshore and the depth of overlying water and many other factors. All these factors affect the energy required to get that oil to the surface, usually expressed as the Energy Return on Investment or EROI (sometimes EROEI). This concept was explicitly derived initially by ecologist Hall in his PhD work on migrating fish (Hall 1972) and applied later to oil and other fossil fuels (e.g. in Hall and Cleveland 1981; Cleveland et al. 1984; Hall et al. 1986; and Hall et al. 2014). The idea of the energy cost of energy and its importance to human culture had previously been expressed earlier by Anthropologist Leslie White (1943), Sociologist Fred Cottrell (1955), and Ecologist Howard Odum (1971).

The EROI of our most important fuels is declining and most renewable and non-conventional energy alternatives tend to have substantially lower EROI values than traditional conventional fossil fuels, especially if the needed corrections for intermittency at high penetration are included (Palmer 2017; Hall 2017). At the societal level, declining EROI means that an increasing proportion of energy output and all economic activity must be diverted to attaining the energy needed to run an economy, leaving less discretionary funds available for "non-essential" purchases which often drive growth. The declining EROI of traditional fossil fuel energy sources and the effect of that on the world economy are likely to result in myriad consequences, most of which will not be perceived as good.

At this time the reader can take his or her choice as to whether physical, economic or environmental factors will determine the future of oil supplies. Our conclusion is that all will have a strong impact, but that eventually physical supplies will most likely dominate. There is a lot of oil left in the ground, but not a lot of high-quality oil that can be extracted at large energy profit. Meanwhile oil use continues to climb, although much more slowly than in the past. The growth of OECD economies too is also declining, presumably in part to the decline in growth of oil and energy more generally.

Environmental Issues

While our principal concern is with the improper conceptual boundaries of NCE, and the under-appreciated role of energy in our economy, we are also concerned that several of the probably most important economic issues in our future are basically biophysical issues.

Two recent climate reports, the Fourth National Climate Assessment (a report of thirteen agencies of the U.S. government) and the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) analyze the current state of the climate and future threats of the Business as Usual Scenario. The IPCC report's high estimate for warming of the planet is an astounding 6 Celsius, compared to the 1986-2005 baseline. As a reference point, the difference between the baseline temperature, and the average temperature during the last glaciation was also six degrees. At that time a reduction of average temperatures meant that an ice sheet a mile thick covered most of the Northeastern United States. The report asserted, and backed with evidence, that an increase in greenhouse gases (GHGs), especially carbon dioxide from burning fossil fuels, (but also water vapor), was the source of the disruption of the planetary systems. The report concluded that the increased emissions of GHGs would affect all components of the earth system, with an increasing likelihood of severe and irreversible impacts. They called for substantial and sustained decreases in GHGs, and a greater attention to adaptation as well as mitigation (IPCC 2015). The National Climate Assessment predicted global temperature increases of 9 Fahrenheit, or 5 C, with a high-end estimate of 11. This, could produce sea level increases of up to six feet by 2100 increased droughts and wildfires, along with a severe disruption of crop productivity and a decline in the economically vital outdoor recreation industry. The report divided the country into ten different regions and provided details of the different economic and physical impacts of climate change per region (USGCRP 2018).

Biodiversity loss is another issue that is poorly handled by conventional economics. We are learning about our comprehensive dependence on nature in its entirety only recently, for such direct actions such as soil formation, pollination and supplies of fish, as well as more comprehensive but diffuse actions generally known as ecosystem services (Daly 2005). Sometimes a dollar value is attempted for these services, and they tend to be on the same order of magnitude as the total GDP of the planet, although it also has been argued to be infinitely more. Without the operation of nature our economy, and indeed our lives, would cease to exist (Costanza, et al. 1997).

There are other environmental concerns related to the continued use of fossil fuels, probably most importantly related to climate issues, that are important in a world that is increasingly resource constrained while being stressed in many, many ways by continued human population and economic growth --- while we may have less energy to deal with the consequences of the disruptions (e.g. Day et al. 2018). In 2009 a team of scientists headed by Johan Rockström of the Stockholm Resilience Centre published an article in Nature delineating nine "planetary boundaries" of human activity. They conducted painstaking statistical work to compare current levels of environmental impact of human society such as atmospheric carbon dioxide, biodiversity loss, chemical pollution, disruption of biogeochemical cycles, freshwater use, and land-use changes. They concluded that three of these boundaries have already been exceeded (biodiversity loss, atmospheric CO_2 and the disruption of the nitrogen cycle. If this process continues the stability of the Holocene epoch, in which human society evolved and thrived, is likely to disappear. The new Anthropocene epoch is likely to be significantly different, and more chaotic, than anything our species has ever seen. To this, we might add, that they will occur in a time frame in which we will likely see the end of the widespread use of fossil fuels which today are often used profusely to overcome, mitigate or rebuild in response to existing environmental problems. Meanwhile we must recognize that any excessive personal affluence is not purchased just with hard work but also with great impact on the environment.

History of BioPhysical Approaches to Economics

Historical approaches to the study of biophysical economics have been part of its methodology since the earliest publications. Over time, our understanding of prior economic writers has become more sophisticated and better linked to the processes of nature, as well as to the dynamics of economic phenomena.

While the emergence of BioPhysical economics as a named entity is a relatively new phenomenon, the ideas developed within have ancient origins. Writers such as Plato commented upon the relation between environmental integrity and soil depletion in works such as *The Republic* and the *Dialogue of Critias*. Medieval writers also advocated economic institutions that would maintain the pastoral hierarchies of the feudal era. By the 1600s, mercantile pamphleteers expounded the benefits of expanded trade in the era of hand-dug mines (mostly by slave labor) and wind power to propel sailing ships.

More generally nearly all early economists, as reviewed below, had at least some understanding that wealth came originally from nature (often referred to as land), was often generated with the active (energy-based) application of labor, and somewhat later, that other forms of energy such as wind or coal were likewise critical.

It was not until the later days of the era of the long-distance trader that political economists began to express interest in the origins of value and wealth, and it was not until the age of fossil fuels and the industrial revolution that the idea of the self-regulating economy emerged. In 1690 William Petty, a transition figure between the ages of mercantilism and classical political economy declared, in *Political Arithmetic*, "Labour is the Father and active principle of Wealth, as Lands are the Mother."

Classical Political Economy, which is what economics was first called, spanned the time from the mid-1750s to the early 1870s. All classical political economists shared several points in common: 1) that value, and therefore price, was determined by the costs of production, most prominently the human labor time needed to transform the material of nature into objects of use for humans. 2) All wanted to influence public policy. 3) All were interested in explaining the mechanisms of accumulation, growth, and the origins of wealth. 4) Nearly all, except for John Stuart Mill, lived in an age when production and wealth were limited by the ability to capture the solar flow. Consequently, all believed that this would lead to the eventual onset of a stationary state, when the internal dynamics of the economy would result in the end of economic growth.

The first group of classical political economists, called the Physiocrats, believed that the source of value and wealth was in the land and the agricultural labor that transformed it. Only the land, with its photosynthetic capabilities, could create new value. The Physiocrats considered manufacturing workers to be "sterile," as they only transformed the products of nature. Electromagnetic energy and the nutrients of the soil did the real work. A tiny aristocracy appropriated not only the products of the luxury shops, but the bulk of agricultural output as well. The Physiocrats linked production and circulation together in the famous *Tableau Economique* and used the model to argue to Louis XV of France that the wealth of the farm should be reinvested in developing large-scale commercial agriculture. They were ultimately unsuccessful, although land reform would arrive in the aftermath of the French Revolution.

On the other side of the English Channel, Scottish moral philosopher Adam Smith developed a more general theory of the origins of wealth, based upon the greater manufacturing capabilities of the British Isles. He held that the origins of wealth could be found in the number of productive laborers and the individual productivity of each worker. Labor productivity and efficiency, before the age of fossil fuels, could be enhanced primarily by organizational means. Smith based the increase of productivity and wealth on specialization and the division of labor and tied the expansion wealth to a regime of free trade. For Smith, the origins of value were in the amount of human labor needed to produce a commodity that had value in exchange. While Smith believed strongly in the material benefits of a "system of perfect liberty," he also thought such an economy would eventually mature and run short of investment opportunities. This would result in the end of economics growth, or a "stationary state." Smith found this prospect frightening, as life in the non-growing economy would be "melancholy."

Classical Economists and Their Connections to BioPhysical Economics

In the early 1800s two prominent English-speaking economists, David Ricardo and Thomas Malthus, debated the economic effects of limiting imports of cheap grains (which they referred to as "Corn") into Britain. For both the primary goal of political economy was to explain the "laws" of distribution, and the debate over the Corn Laws, which restricted agricultural imports, provided a practical and political backdrop to their debates. Ricardo argued that import restrictions insured that poorer quality and less fertile land would have to be put into production, thereby raising prices and wages, as well as all costs to business. This would hasten the onset of the dreaded end of accumulation known as the stationary state. It was during this argument that Ricardo enunciated the "best-first" principle as well as the principle of diminishing marginal returns. These principles would be the basis of not only neoclassical production theory, but the later BioPhysical economists' theories of peak oil and the decline of resource quality as well. The repeal of the Corn Laws, allowing the influx of grain from more productive France, would bring lower food prices, reduced business costs, and an increase in growth and accumulation (although a net loss of power of the land-owning aristocracy). Ricardo was elected to Parliament and he argued as if his very life was at stake for the repeal of the Corn Laws. As it turns out, Ricardo's life was at stake. He died in 1823 while working on integrating mechanization into the labor theory of value, and never lived to see his vision implemented. The Corn Laws were not repealed until 1846.

Malthus argued that the primary reasons for economic troubles were populations that increased more rapidly than did their food supply, and a lack of effectual demand, or demand backed by money. To control population growth Malthus advocated "courting the return of the plague and keeping doctors from attending to the poor". To limit the possibility of stagnation due to overproduction, Malthus advocated for a redistribution of income and wealth from the rising capitalist class, who tended to oversave, and remove money from the economy, to the aristocracy, who would spend the money on non-productive servants and retainers and build monuments to themselves. Malthus sought to institute these policies, rather than repeal the Corn Laws. Despite being a man of the cloth, he was not full of Christian charity, as he believed that it eventually caused more misery. Neither was Malthus particularly scientific, as he offered no empirical evidence of population increasing faster than did the food supply.

One thing was clear in the writings of the early classical political economists. As long as the primary source of energy was the limited photosynthetic capacity of the land, the lot of the majority of humankind would be a meager, close to biological, subsistence. Later, in the 1890s, neoclassical economist Alfred Marshall would argue that when capital was the primary factor, production would exhibit increasing, rather than diminishing, returns. BioPhysical economists attribute this increase in output to the harnessing of fossil fuels (i.e. a biophysical issue) instead of some miraculous property of the abstract, and difficult to measure, concept of capital.

The first political economist to understand fully the role of fossil fuels in augmenting the increase in labor productivity and the accumulation of capital (a very BioPhysical concern) was the German Philosopher, Karl Marx. While most economists of the past and present define capital as a thing, such as a machine (or more broadly, means of production) or a quantity of money by which one can purchase means of production, Marx defined capital as a process, more precisely the "self-expansion of capital." Capitalists would begin with money, buy means of production and labor power (the ability of human beings to work), enter a process of production, sell the resulting products, and realize more money that they began with. Marx called this additional increment "surplus value". Capitalism depends upon the extraction of surplus labor and its reinvestment in expanding the production process. From the Marxian position the idea of a no-growth, steady state, form of capitalism is oxymoronic. Marx realized, and expressed in the first volume of Capital, that human labor, on its own, could create nothing (Marx, 1976). Human labor could only transform the products of nature. The metabolic combination of actual human labor, with all its variation and diversity of culture and skills, and nature could produce use values (or products useful to human beings.) These use values were the source of wealth. It was abstract labor (devoid of any specific content) that produced exchange value, which was the basis of price. Like other classical political economists, Marx argued that use value had no role in the determination of price, but every role in the determination of wealth! Marx also realized that humans cannot perform labor without being supplied with (food) energy and rest. Machines can also degrade with either overuse or disuse (i.e. rust). This makes Marx's theories of value consistent with both the first and second laws of thermodynamics.

Because Marx understood the role of energy better than those who wrote solely in the era of the solar flow, he did not see a lack of energy as the prime determinant of periodic crises. Energy is not a magical incantation, but works through social processes, most prominently its effect upon increasing labor productivity. Unlike other classical political economists, Marx did not believe the ultimate fate of a capitalist economy was in the stationary state. Access to fossil energy simply transcended the limitations of the solar flow and the photosynthetic capacity of the land. The fate of most people did not have to be a meager subsistence yielded by a stingy nature and an even stingier aristocracy. Instead of a steady state Marx emphasized periodic crises grounded in the dynamics of capital accumulation. In the beginning of a business cycle investments in fossil fuel powered means of production would call forth vast increases in productivity, leading to increases in the rate of profit. However, in the later stages of the cycle, investments in machinery and energy would outstrip the rate of increase in labor productivity. This would cause profits, and investments, to fall and touch off a period of economic decline. In the subsequent depression, bad investments would be written off and desperate unemployed workers would be willing to work harder for less. Conditions for profitability would be restored in the trough and another cycle would begin anew. Appropriating a phrase from Newton, Marx termed this process a "law of motion of capitalism." He also contended that weaker firms that failed in the depression would be bought up by the stronger, and historical progression would lead to monopoly concentration (Marx, 1981).

In the hands of Ricardo (1962), the labor theory of value was a clarion call and justification for the replacement of an idle aristocracy by a vibrant and expanding capitalist class. In the hands of Marx, the labor theory of value became a tool for understanding how the rule of the capitalist class would be replaced by that of workers as associated producers, in other words, socialism. It should not, therefore, surprise anyone that those in power wanted to replace the labor theory of value with another theory that justified the perpetuation of capitalism as a universal and beneficent system. Within four years of the publication of the first volume of Marx's *Capital* there appeared a new approach to the theory of price and value. The labor theory of value, which depended upon an objective counting of the costs of production, most importantly human labor, was replaced by a subjective theory of utility. The classical distinction between use value and exchange value evaporated, and now use value (recast as utility) emerged as the basis of exchange value or price. This approach, originally called marginalism, became the basis of what we now know as neoclassical economics.

Marginalism was enunciated almost simultaneously by three economists in three different nations in the early 1870s. In 1871 the English economist/Engineer William Stanley Jevons published *Theory of Political Economy*, although he first advocated his ideas on marginal utility in a series of papers read before the Royal Society as early as 1862 (Black 1974). The year 1871 also saw the publication of Carl Menger's *Principles of Economics*, which was followed in 1874 by *Elements of Pure Economics* by the Francophone Swiss economist Leon Walras. All believed that one could understand the economy simply by concentrating on the process of exchange. Production, upon which all classical political economists based their analyses, did not even enter the world of pure economics according to Walras. For these theorists, value and price were determined by subject desires of consumers, and value, like beauty, was in the eye of the beholder. Total utility, or satisfaction, or well-being was derived solely from the consumption of goods and services purchased on the markets. But price was determined by marginal utility, or the extra satisfaction achieved by consuming one more unit of goods or services. Jevons called this the final degree of utility while Walras referred to it as rareté. This focus fit nicely with the use of mathematics. Although Menger did not cast his analysis mathematically, both Jevons and Walras were trained as engineers. The marginal change in utility with respect to an infinitesimal change in consumption fit within the framework of differential calculus and theoretical mechanics. Jevons went as far as to call economics "the mechanics of utility and self-interest."

Marginalist economists had to make several abstract assumptions in order to constrain human behavior to that which could be analyzed by means of differential calculus. People were declared rational and self-interested with self-regarding preferences. Utility was endemic to each individual and one could not compare interpersonal utility. Humans were also considered insatiable in their desires. If an object brought utility, more of it resulted in more utility. Neoclassical economist, and creator of Welfare Economics, Arthur Cecil Pigou called this the "Piggy axiom" More is always preferred to less. However, utility declines on the margin. While the first unit of a good, say water on a hot day, would bring a high level of utility, extra drinks would bring increasingly less. People would be willing to pay less as marginal utility declined. After a few mathematical machinations (it is hard to aggregate utility if you cannot even compare it) the result was a downward-sloping demand curve. In the 1890s neoclassical economics was born when the process of production was put on a marginal utility basis with the publication of *An Essay on the Coordination of the Laws of Distribution* in 1894 by the English economist Philip Wicksteed, and by John Bates Clark in the United States in 1895 in *The Distribution of Wealth*. The theory of production and the theory of distribution became one and the same. Each factor of production earned its marginal product, and the total output was exhausted in factor payment, eliminating the possibility of exploitation. Capitalism was hereby rendered fair. The same mathematics that one used to derive a demand curve from marginal utility (a Lagrangian multiplier or a total differential) allowed the economists to derive the supply curve from marginal productivity. All that was needed was for English economist Alfred Marshal to put supply and demand together in his 1890 *Principles of Economics* and argue that it takes both blades of a pair of scissors to make the cut. Now price was determined in the sphere of exchange by the interaction of supply and demand and price competition among competitive firms. Neoclassical economists could be confident that, in the end, Say's Law of Markets would prevail -- where the process of creating goods and services would also create the incomes needed to purchase them in the form of factor payments (wages, interest, profits, rents) that were equal to the factor's marginal product. Consequently, there could be no lack of effective demand. Depressions were theoretically impossible.

From a BioPhysical perspective, economics became analytically divorced from its material base. The absolute scarcity of energy and resources was relegated to the peripheries of economic theory, to be replaced by the relative scarcity resulting from the insatiable desires of humans. But can such a theoretical perspective be viable in the second half of the age of oil? Evidence from scientific studies such as Rockström's indicate the transcendence of at least three planetary boundaries so far. If humans are truly insatiable, how can we possibly live within nature's limits, especially since a system in overshoot cannot grow its way into sustainability.

While analyses of material and energy flows can be found in input-output analysis (e.g. Miller and Blair 1985) such techniques are rare and rather far removed from the basic neoclassical conceptual model or its usual applications. Especially comprehensive analyses of the role of energy in our society were undertaken using input-output analyses in the 1980s by modelers such as Bullard, Hannon, and Herendeen. Miller and Blair review these studies quite favorably. Such studies find that the quantities of energy required and their general importance to economic production are far more complex than is usually assumed by economists. Energy is not simply another commodity, with myriad substitutes, but rather an essential factor for production. So at least some conventional economists did appreciate the role of energy.

Relation of Classical to BioPhysical Economics

In *Energy and the Wealth of Nations* we critiqued the behavioral assumptions of neoclassical economics that are maintained instead of tested and are done so in violation of the laws of thermodynamics. Our perspective is based in part on the work of behavioral economists who have tested the assumptions of neoclassical economics and found them wanting (e.g. Gintis 2000). Here we must add another myth: that equilibrium prices are determined by the interaction of supply and demand in impersonal and competitive markets. Nearly every student in principles of economics is subjected to this myth. Many believe it unequivocally. However, those familiar with the world of corporate decision making are likely to understand that prices are most often set administratively. Corporations with enough market power determine their prime costs (energy, materials, labor), then figure out what profit rate they must achieve in order to acquire enough access to finance, then set prices accordingly.

By the 1920s neoclassical economists were extending the supply and demand model to the macroeconomy as a whole arguing that one can analyze the entire economy as if it were a single, competitive firm. The view is still held widely among neoclassical economists, especially growth theorists. For example, the labor market would achieve equilibrium when a downward sloping demand curve (companies would hire fewer workers as wages rose) intersected an upward-sloping labor supply curve (workers would provide more hours at higher wages). The market insured that an equilibrium wage would also produce full employment. If unemployment were to exist, it was the result of wages in excess of equilibrium. Therefore, the cure for unemployment was a reduction in wages. Finance markets were seen in a similar light. Levels of savings and investment depended upon the interest rate, or the price of money. Markets would, by themselves, find the proper interest rate to balance savings and investment, thereby assuring a well-functioning credit market.

The data indicated a very different outcome in the 1930s after a global financial collapse and unemployment rates that reached 25% in the United States, and in excess of 50% in Germany. In 1936 a British economist by the name of John Maynard Keynes published his epic *General Theory of Employment*, *Interest and Money*. Keynes rejected Say's Law and the notion that wages are determined by in intersection of the marginal utility of the wage and the marginal disutility of the work. He then constructed an elegant theory that showed that macroeconomic equilibrium, and therefore no tendency to change, could be achieved at any level of output, including high unemployment levels of output. He attributed the high unemployment levels of output to a lack of aggregate demand and suggested a program of public works and easier credit to allow the return of production levels that would also produce full employment. Keynes considered himself a moderate conservative who wanted to save capitalism from its own worst nightmare, unsustainable levels of unemployment and poverty. Keynes found the alternatives available in Europe at the time, Bolshevism and fascism, to be highly unpalatable. In the post-war world, especially in the United States, Keynesian economics became associated with policies that pursued economic growth. In the world economy the victorious and hegemonic United States maintained a dominant military and the only viable industrial economy in the world and was able to dictate the terms of international finance by means of several institutions established at the International Monetary Conference in Bretton Woods, New Hampshire, such as the International Monetary Fund, the World Bank, and the General Agreement on Tariffs and Trade. This allowed the U.S. to buy in a buyer's market and sell in a seller's markets. In a historically unprecedented agreement American Corporations, flush with profits, agreed to share some of them with unionized industrial workers. Moreover, the U.S. was the world's largest oil producer. The postwar economy, especially the automobile market and suburban housing was built on cheap gasoline and rising incomes. The United States economy was in its Golden Age. However, few economists asked about the energy basis of this economic bonanza, a concept later emphasized by biophysical economists (e.g. Cottrell 1955; Odum 1971; Georgescu-Roegen 1975; Hall and Klitgaard 2018).

In the early 1970s the structural pillars of Golden Age prosperity began to crumble (Day et al. 2018). The U.S. could not achieve a military victory in Southeast Asia. Germany and Japan caught up with, and in some ways surpassed, the United States as an industrial producer. Domestic oil peaked, and the U.S. became vulnerable to international oil price fluctuations, punctuated by two energy crises in 1973 and 1979. Since the peak of oil production in 1970, every oil price spike has been followed by a recession, (See Fig. **4**), the Bretton Woods System collapsed, and economic growth rates slowed (Hall and Klitgaard 2018). Moreover, stagnation and the highest unemployment rates since the Great Depression occurred simultaneously with double-digit inflation. What did this mean for economic policy? Keynesian economics lost favor when it could not explain stagflation, which, incidentally, BioPhysical economics had less trouble in doing (Hall et al. 1986). Neoclassical economics once again dominated the profession. However, the maintained hypotheses and behavioral postulates of neoclassical economics violate the basic principles of thermodynamics and is inconsistent with the advances in other behavior sciences. They also result in the huge dislocations and concentrations of wealth discussed at the start of this piece. We believe it is time for a new theory grounded in the unity of natural and social sciences. We call this theory BioPhysical Economics.

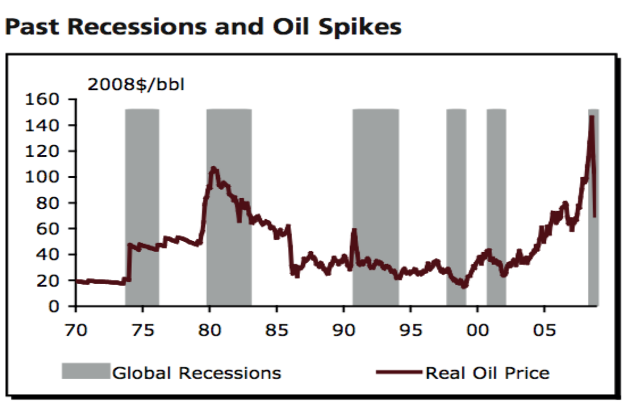

Fig. (4). Relation of oil price spikes and recessions for the United States.

The Origins and Development of BioPhysical Economics

The term BioPhysical Economics first appeared in a 1984 paper by Cutler Cleveland, Robert Costanza, Charles Hall, and Robert Kaufmann in the respected journal Science. In this article the authors argued that the goals of stable prices, full employment, and economic growth were not met after the 1970s because of a decline in resource quantity and quality. In the initial paper the authors presented strong econometric evidence (R^2=0.98) that output is linked to fuel use, and that the increase in labor productivity was due to an increase in energy use, directly and indirectly as embodied in capital equipment. Their analysis was based in part on the concept of a general and continuous decline in Energy Return on Investment (EROI), and they concluded that the lack of alternative high-EROI energy resources will limit future economic growth. Hall, Cleveland and Kaufmann followed their 1984 paper with a book entitled *Energy and Resource Quality: The Ecology of the Economic Process*. This book chronicles former economic and ecological thought and provides detailed analyses of the EROIs of different fuels. The book ends with an editorial critiquing the use of conventional (neoclassical) economics as the sole metric of economic success and warns readers of possible future declines because of declining resource quality.

In 2001 Charles Hall and colleagues published a paper in BioScience titled "The Need to Reintegrate the Natural Sciences with Economics" (Hall et al. 2001). They argued that wealth is not created in markets, but in the natural world and the energy-requiring processes that upgrade matter. Essentially all economic processes must obey the laws of science, especially the laws of thermodynamics. They presented a strong critique of neoclassical economics that subsequently became a fundamental part of the canon of BioPhysical economics: That neoclassical economics is inconsistent with the laws and methods of science. The article includes a critique of the previously mentioned mainstream neoclassical growth theory, derived from the work of Robert Solow, that was based on labor and capital but ignored energy in the specification of the production function. As a result, a large unexplained residual (in excess of 50 percent) appeared in econometric estimates (Solow 1957, Dennison 1989) that neoclassical economists attributed to technological change, also known as total factor productivity. The biophysical authors found that including energy in the production function made the residual virtually disappear (Kummel et al., 2002). They also found that energy was more important than labor and perhaps capital. Research on the efficacy of using aggregate production functions and the meaning of total factor productivity continues to this day.

Hall and Klitgaard (2006) was the first published collaboration between the present authors in an article entitled "The Need for a New, Biophysically-Based Paradigm in Economics in the Second Half of the Age of Oil." They called for an integration of the methods of economics and biophysical sciences. As much as economists try to distance themselves from other social scientists, and adopt the mathematical formality of theoretical mechanics, the method of deduction from maintained and untested hypotheses about human behavior and market structure remain problematic. However mathematical sophistication alone is not sufficient. Economic analysis should include the important role of energy -- as well as other resources, more explicitly. They concluded that important decisions about the interaction of nature and the economy should not simply be left to market processes.

The year 2011 was a watershed in Biophysical economics, as at least 21 papers appeared in professional journals, from "Ecological Economic Reviews," published by the New York State Academy of Sciences, to the journal Sustainability. David

Murphy and Charles Hall presented evidence that the long-term economic slowdown and the financial crisis of 2008-2009 could be attributed to changes in energy supply and fuel prices. Myriad papers refining the measurement of Energy Returns on Investment appeared in a special issue of Sustainability, edited by Charles Hall. Kent Klitgaard and Lisi Krall began to explore the internal dynamics of the processes of growth and accumulation in a capitalist economy. They argued that the inner essence of a capitalist economy is based on economic growth, and that a steady-state economy would result in prolonged to permanent depression if society's institutional structure were not changed. Kent Klitgaard followed this with an article commemorating the fiftieth anniversary of the publication of *Monopoly Capital*, by Paul Baran and Paul Sweezy (1966). He first summarized Baran and Sweezy's argument that the U.S. economy is dominated by large corporations that do not engage in price competition. This lack of price competition leads a large economic surplus to accumulate. If this surplus is not spent, or absorbed, the economy stagnates. Klitgaard argues that the traditional methods of surplus absorption, made possible with cheap fuels, such as conspicuous consumption and outright waste, are incompatible with a long-run sustainable future. In 2018 Hall and Klitgaard published the second edition of *Energy and the Wealth of Nations*. It is our most comprehensive effort at integrating the analyses of biophysical sciences with institutional and heterodox political economy. The authors argued that economics must be consistent with how nature works and with how actual economies work. They proposed that the end of the fossil fuel era will not be an easy one, but that humans are resilient and adaptable creatures. There is room for concern, but reason for hope as well. Meanwhile the International Society for BioPhysical Economics has had well attended annual meetings since 2008, and many other excellent papers have been published (e.g. King et al. 2015; Court and Fizzaine in press); Giampietro, various years).

BioPhysical Economics Today

Presently there are roughly several hundred people directly involved in understanding or applying biophysical economics, and a thousand or more interested as indicated by list serves on the topic. Formally many are members of the International Society of BioPhysical Economics (ISBPE) which has had 10 annual meetings. BioPhysical economists publish in various scholarly journals including *Science* and *Nature* and more specialized Journals such as *Energy Policy*, *Energy*, *Sustainability* and *BioPhysical Economics and Resource Quality*. Topics frequently considered are the relation of energy and material use to economic activity, physical resource supplies into the future (e.g. peak oil), issues of resource quality, historical estimates of EROI and the causal links between energy availability and cost and the dynamics of capital accumulation. Of particular interest among many investigators is the determination of the degree to which renewable technologies, such as photovoltaics and wind turbines, can take over from more carbon-intensive fossil fuels. As part of this endeavor investigators are calculating the EROI of different technologies and the energy cost of dealing with the intermittency of renewables, including the costs of storage and redundancy (e.g. Palmer, 2018). Other interests include the material requirements for given levels of electricity production and the possibilities or lack thereof of displacing diesel with electricity for truck transportation. From the economic perspective researchers are developing more sophisticated critiques of macrodynamics, especially the efficacy of using aggregate production functions, and looking more deeply into the complex evolutionary patterns and the role played by the transition from production for subsistence to the production of surplus. In this time the effort to integrate energy analyses from the perspective of social and natural sciences has continued unabated. Much progress has been made, but much work remains to be accomplished.

In a sense, all of biophysical economics is asking some version of the basic questions put forth in *The Limits to Growth* in 1972. To what extent will biological and physical resources interact with economic behavior in complicated feedback mechanisms? How will humanity adapt to the potential conjuncture of catastrophic climate change and the end of the fossil fuel era? While many would argue, and we would not disagree, that modern economies and technologies have generated unprecedented global affluence (e.g. Roser, 2017), this does not apply for the world's poorer half. BioPhysical economists believe that the present affluence sits very precariously on a bubble of oil (and other fossil fuels) whose future is extremely uncertain at best (e.g. Mohr et al. 2015). Can we bring the poorer half of the world out of poverty without further depleting our quality fossil fuels or upsetting the climate? How much can we help the poor by taxing the very wealthy, as is advocated by economists such as Krugman, Stiglitz and Piketty? In an age of climate change and resource depletion it would be seemingly impossible to help the world's poor without the wealthy beginning to live within the planet's limits. Historically, taxation has been the primary vehicle for income redistribution. Contemporary mainstream economics relegates these issues to the peripheries of concern. BioPhysical economics seeks to elevate the concern for the planet, its people, and its resources to a position of primacy, while arguing for greater equitability (Hall and Klitgaard 2017). We have a lot of work to do, starting with how we teach economics.

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