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Economic Growth with Energy

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This paper works out some of the basic properties of an economy with energy as a factor of production. The economy now consists of streams of energy conversions that direct energy to the production of goods and services. The focus on energy generates a variety of insights. It yields a new taxonomy of economies and economic activities; allows a better grasp of the tasks performed by labor and capital; raises the prospect of examining growth as the speeding up of machines; and identifies greater use of energy as an important source of growth. In addition, we use these results to explain the near stagnation in living standards in agrarian economies in the millennia before 1800, and the dramatic acceleration in growth since that date.

In a departure from neoclassical economics, this paper will develop an alternative conception of the economy that recognizes energy – together with workers, capital and technology – as a factor of production.

The neoclassical construct of the economy is built on three factors of production: capital, labor and technology. Production in each period begins with given amounts of capital, labor and technology, and terminates in the production of goods. Capital has its origins in prior periods: it is simply a portion of the economy's output carried forward from previous periods. The neoclassical economists are generally reticent about how labor is produced or reproduced; they assume that it grows exogenously.[1] Technology is described as the stock of knowledge available to an economy. Knowledge may be embodied in machines, human skills, or it may take the form of social codes and arrangements.

Missing from this account of the economy is the primary force that drives all economic activities: energy. Sure enough, energy enters the neoclassical economy as the effort of labor, but this source of energy has been declining progressively over the past two centuries. Energy from non-human sources – coal, oil, electricity, food or fertilizer – enters the economy only as an intermediate input; it is incorporated into a country's national income accounts as value-added in the energy sector. Quite simply, energy is not a factor of production. In other words, neoclassical economics is built upon a disjunction between the economy and ecology. The neoclassical economy exists in splendid isolation from nature and its well-springs of energy.

Among economists, Nicholas Georgescu-Roegen (1972, 1976) was one of the first to comment on the absence of energy in economic theory. He pointed out

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* I wish to thank Steve Morrison (Northeastern University, Boston) and Salim Rashid (University of Illinois, Urbana-Champaign) for their comments on earlier drafts of this paper.

[1] Recent versions of the growth model endogenize technological change. See Lucas (1988) and Romer (1990).

that Marxists and neoclassical economists abstract from nature; they take resources and energy flows for granted and ignore the economy's output of wastes. Standard economics, Georgescu-Roegen (1976: 30) argued, does not recognize that "terrestrial resources of energy and materials are irrevocably used up and the harmful effects of pollution on the environment accumulate." The economists' optimism about the endless possibilities of growth is based on this truncated worldview that excludes nature from its calculus.[2] Following the lead of Georgescu-Roegen and others, the new field of ecological economics has explored the different ways in which entropy imposes limits on growth.[3]

This papers works out the basic properties of an economy with energy as the driving force behind all economic activities. Once we focus on energy, the economy must be seen as a system of energy flows, a succession of energy conversions, that culminate in the production of goods and services. We ask how this conception of the economy alters our understanding of labor and capital, of growth, and sources of growth. In addition, we will show that this focus on energy facilitates a better understanding of the Industrial Revolution and the explosion in economic growth this has produced since the nineteenth century.

The rest of the paper unfolds in six sections. Section one offers an alternative conceptualization of the economy that recognizes energy as the basis of all economic activities. Section two shows that classical economics implicitly incorporated energy into the economy by recognizing land as a factor of production in agriculture; however, neoclassical economics ignores energy altogether by redefining land as capital. Section three examines how the presence of energy affects our understanding of the functions of labor and capital in the econ-

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[2] Georgescu-Roegen (1975: 370) writes: "…in bioeconomics we must emphasize that every Cadillac or every Zim – let alone any instrument of war – means fewer ploughshares for some future generations, and, implicitly, fewer human beings, too."

[3] See Lawn (2001) and Farley and Daly (2003). It should be noted that environmental economics or resource economics, for the most part, apply the standard neoclassical framework, to the study of the environment or natural resources as sectors of the economy.

omy. Section four examines energy as a source of economic growth. Section five examines how the dynamics of an economy is affected by the nature of the primary source – organic or inorganic – from which it draws its energy. Section six presents a summary of the key contributions of our energy-based framework.

1. *Energy In The Economy*

An economy consists of people effecting changes in the states of the world consisting of energy and matter. Since no change can be effected without the expense of energy, energy is the indispensable force driving all economic activities. Starting with these propositions, it would be difficult to construct a discourse about the economy without talking about the sources, the harnessing, the direction, redirection and use of energy. In other words, we must deal with the economy as an energy system.

This economy is set in motion by primary converting activities (PCAs), the only activities that make a net contribution of energy to the economy. These activities convert energy from naturally occurring sources – solar heat and light, wind, running water, tide, minerals, fossil fuels, gravitation and chemicals – into forms that will eventually be used to produce good and services. A list of primary converters would include plant and animal life in all its forms; power plants using coal, oil, gas or water; wind, water and tide mills; atomic plants; photovoltaic cells; weapons using explosives; etc. The PCAs yield a net supply of usable energy to the economy.[4]

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[4] It should be noted that no complete chain of energy conversions, starting with the extraction of energy from nature and leading eventually to usable energy flows, will be undertaken unless its yield of usable energy is greater than the usable energy that is expended in the different stages of energy conversion. In other words, taken together, the system of energy conversions must produce a surplus of usable energy for use in production and consumption activities. It is this energy-producing sector that is the driving force behind the economy.

The PCAs do not always deliver energy in forms that can be used directly in the production of goods and services; they have to be converted and re-converted into more usable forms – or delivered to points where they will be used – by secondary converting activities (SCAs). A few examples of SCAs may be helpful. Most foods have to be processed before they can be consumed by humans and animals. Similarly, many activities use electricity only after converting it into heat, motion, sound, light, electro-magnetic energy, chemical energy, etc. By far the most important set of SCAs are performed by humans, who process food into motion and neural energy. It is important to note that SCAs do not make any net contribution of energy to the economy.

In addition, a third set of activities produce goods and services that do not deliver energy inputs to other activities. This category includes all primary-producing activities that extract non-energy producing raw materials, such as metallic ores, rocks, sand and fibers; activities that process these raw materials; transportation of people and goods; and services. In mature industrial economies, these activities employ the bulk of the labor force.

A simpler, two-fold taxonomy of activities may also be useful in some circumstances. This breaks down the economy into energy-producing activities and all other activities that do not deliver energy inputs. Other things remaining the same, the living standards in an economy will vary inversely with the share of the labor force employed in energy-producing activities.

2. *Energy in Classical and Neoclassical Economics*

Although the classical economists did not explicitly recognize energy *per se* as a factor of production, they understood clearly the limits which land (nature) imposes on economic activities, especially in agriculture. Standing on this insight, they divided the economy into two distinct sectors: agriculture and manufacturing. This distinction deeply informs the classical theory of economic growth.

The classical economists explored the contributions of land to the economy in order to explain the presence of a surplus, over and above the cost of labor and capital, in agriculture.[5] Adam Smith's explanation of this surplus was direct: in agriculture, "nature labors along with man," whereas in manufactures "nature does nothing; man does all."[6] When classical economists speak of the "fertility of nature" (Adam Smith), "the productive and indestructible powers of the soil (David Ricardo)," "the natural and inherent powers of the soil (John McCulloch)," or speak of the earth as "a wondrous chemical workshop wherein many materials and elements are mixed together and worked on (Jean-Baptiste Say)," their language conveys a clear understanding of the energy that nature contributes to the economy.[7] In a similar vein, John Stuart Mill (1848: 23) wrote that matter contains "active energies by which it cooperates, with, and even be used as a substitute for, labor." Likewise, Frédéric Bastiat (1850: 9.16) identifies the different forms in which energy – as light, heat, electricity, plant life, wind, elasticity, gravitation – contributes to production, but he sees these forces at work both in agriculture and manufacturing.[8]

The classical theory of the macro-economy incorporated these insights about the "powers" of nature in three steps. First, the classical economists broke down their economy into two sectors, agriculture and manufacturing. Second, they defined the distinctness of agriculture by recognizing that labor and capital in

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[5] The Physiocrats too asserted that agriculture was the only activity that produced a net product above and beyond the payments made to capital and labor. Brue (2000: 39).

[6] Adam Smith (1776: II.5.12) writes: "The capital employed in agriculture, therefore, not only puts into motion a greater quantity of productive labor than any equal capital employed in manufactures, but in proportion, too, to the quantity of productive labor which it employs, it adds a much greater value to the annual produce of the land and labor of the country, to the real wealth and revenue of its inhabitants."

[7] Frédéric Bastiat (1850: 9.24, 9.32, 9.35, 9.55).

[8] Frédéric Bastiat (1850: 9.16) writes: "Just as the land has light, heat, electricity, plant life, etc., to aid it in producing value, does not capital likewise call upon the wind, elasticity, gravitation to co-operate with it in the work of production?"

this sector worked with land, a third factor of production. Third, they assumed that land was available in fixed quantities, and, in some formulations, its quality was variable. The fixed supply of land produced a tendency towards diminishing returns to capital and labor in agriculture.[9] The presence of diminishing returns – to labor and capital – in agriculture sums up the constraints that nature imposes upon the organic economy. As we shall see later, this classical theory was quite successful in describing the dynamics of economies before the Industrial Revolution.

The neoclassical economists do not admit energy into their macro-economic framework, not even implicitly. This flows from their rejection of land as a factor of production; they subsume land under the rubric of capital.[10] In banishing land from their macro-economic framework, the classical economists are effectively severing the economy's links to nature, thereby excluding energy as a factor of production from the economy. In the absence of land, there is no rationale to divide the economy into two sectors either.

The neoclassical economists treat energy as a raw material or intermediate good. The energy-yielding products – such as oil, electricity or fertilizer – are analytically equivalent to glass, steel, timber or raw cotton. This is problematic. It ignores a fundamental distinction in the function that energy and matter perform in the economy. Oil provides the energy – the agent of change – that drives the processes that convert iron ore into iron, steel, and eventually into thousands of final steel products. Energy drives the work that converts raw materials into final products.

The neoclassical decision to drop land as a unique factor of production was perhaps motivated by the need to explain the new era of sustained growth that began in the nineteenth century. Classical economists could not explain sustained growth; in the long run, their economies ended up in the stationary

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[9] In the presence of land of uniform quality, the tendency to diminishing returns comes into play once all the available land has been brought under cultivation.

[10] Land in nature is not productive until it is *developed* by labor and capital, at which point it becomes capital.

state, characterized by constancy in the stocks of labor and capital. However, instead of recognizing that sustained growth was being fuelled by the infusion of energy from an exogenous source – fossil fuels – the neoclassical economists chose to suppress land as a factor constraining growth. This they accomplished by redefining land as capital. An economy with only two factors of production – capital and labor, both capable of indefinite extension – could escape from the specter of diminishing returns. At least, extensive growth, with both capital and labor growing in tandem, could now occur indefinitely.[11]

Of course, banishing land from the production function creates its own problems for neoclassical economics. Wrigley (1992) has shown that the two-sector model of the classical economists was quite successful in capturing the essential dynamics of pre-industrial economies – characterized by endemic poverty – which derived their energy from organic sources. Once the neoclassical economists had dropped land from their economy, their redefined one-sector economy could not explain the near-stagnation and endemic poverty of organic economies before and after 1800. This would now be explained by invoking cultural and institutional barriers that blocked savings, capital accumulation and technological change.

2. *What Do Labor And Capital Do?*

Although economics textbooks identify capital and labor as factors of production, they say very little about what the two factors contribute to the production of goods and services.[12] Textbook definitions of labor and capital are at best

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[11] We know from Solow (1956) that the neoclassical economy too – with diminishing returns to capital as capital-intensity rises – will settle into a steady-state with just enough capital accumulation to offset the growth of labor.

[12] Stanley Brue's (2000) popular text on the history of economic thought, now in its sixth edition, contains no entry for 'factors of production.' Another more venerable text on the history of economic thought, Mark Blaug (1986), in its fourth edition, contains an entry for 'factor of production: defined,' but neglects to offer a definition.

perfunctory. They define labor as effort, measured as hours of labor; and capital is defined as a produced or 'man-made' factor of production. It is odd that labor is defined by its function, whereas capital is defined by *who* produces it. Presumably, this differentiates capital from labor: as if labor is a naturally occurring factor of production, not a product of the economy.

There are other inconsistencies in the way that economists define factors of production. Although draft animals ranked second to humans as prime movers in the economy, they were not incorporated explicitly into the framework of classical or neoclassical economists as a separate factor of production.[13] In some classical writings, the draft animals were lumped with the wind- and watermills – other prime movers in the economy – as capital. Thus, Adam Smith (1776: II.1.10) treats the "price or value of laboring cattle" as part of the farmer's "fixed capital in the same manner as that of the instruments of husbandry… " By this logic, if all labor were performed by slaves, "laboring" humans too could be treated as part of a firm's fixed capital.

Defining the functions of labor and capital is more straightforward in the framework of an energy-based economy. Indeed, their functions are defined in relation to energy. Both capital and labor perform the same dual supporting functions in the energy economy. In different ways, they (i) convert energy flows, and (ii) control – direct and manipulate – the usable energy to produce goods and services. In other words, capital and labor both supply energy and determine the manner in which it is used.

Two types of energy conversions occur in the economy: organic and inorganic. The first is the work of living organisms; the second occurs through the agency of inorganic matter. Organic conversions begin with plants, which convert the sun's energy into organic compounds. In turn, animals convert the energy they obtain from plants into a new set of organic compounds that produce body heat, mental activity, and kinetic energy. In the economy, humans stand

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[13] According to Smil (1994: 226), in 1800 draft animals supplied a little more than 15 percent of all the energy of all prime movers in Europe.

at the apex of this chain of organic conversions. Through much of history, the chief output of human converters was kinetic energy. They were also the chief source of kinetic energy in the economy before the twentieth century.

The inorganic conversions in nature take many forms. Most importantly, the sun transfers heat to the earth's crust, which, in turn, produces massive flows of kinetic energy in the form of winds, storms, clouds, rain, rivers, waves, and ocean currents. The moon produces tides. Over millions of years, the earth's gravity has acted upon organic matter to transform it into fossil fuels, coal, oil and gas. To this chain of converters, humans have added a variety of devices – capital goods – that pick up the chain of conversions where nature leaves off. The objective of these new converters is to transform energy into forms that are directly usable in economic processes. For lack of a better term, we shall refer to this class of man-made energy-converting devices as synthetic converters.

The synthetic converters are more versatile than humans. As converters, humans are capable of transforming a very limited range of organic substances – some plant and animals foods – into kinetic and neural energy. Inorganic converters today effect a more extensive range of energy conversions. For instance, steam engines convert wood (as fuel) into kinetic energy; steam engines and internal combustion engines convert inorganic substances (fossil fuels) into kinetic energy; wind and water mills harness the kinetic energy available in nature for use in the economy; turbines convert kinetic energy into electricity; and electric motors convert electricity into kinetic energy. The last two converters have greatly increased our ability to transport flows of energy to points where they can be harnessed for work.

The versatility of synthetic converters is a recent phenomenon. Perhaps, the most ancient energy converters were boats carried downstream by river currents, followed by sailing ships. Water-mills appeared in Rome during the first century BCE but it took another five centuries before they spread to the Mediterranean world.[14] Windmills first appeared in what are now eastern Iran and

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[14] Smil (1994): 225.

Afghanistan in the early Islamic period, and spread to Western Europe in the twelfth century.[15] In the period since the eighteenth century, several new converters have been added, including the steam engine, steam turbine, internal-combustion engine, and the nuclear reactor. The discovery of electricity has produced a proliferation of converters, such as the electric motor, light bulb, radio, telegraph, telephone, fax machine, television, computer, etc.

Humans perform a second economic function managing energy flows. These thinking agents, together with their ability to execute intricate kinetic motions, their hearing, sight and speech, are endowed with a vast array of *directive* powers over their own energy flows, as well as those of other humans, draft animals, and all synthetic converters. Beyond directing these energy flows, humans have the potential to use their mental faculty to continually modify the workings of energy systems in order to enhance their efficiency. It is only since the early 1800s, as the economy's energy systems have become more complex, that growing numbers of people have begun to devote an increasing portion of their time to these managerial and creative functions.

In executing their directive functions, humans often take recourse to a variety of tools and coded instructions. Consider how a hammer, one of the oldest and simplest tools, enhances the muscular energy in a woman's arm. If the objective is to strike a nail, a woman can accomplish very little with her bare hands unless the nail has a large flat head. She will be a great deal more effective if she strikes the nail with a hard object, say a rock picked from the surroundings. However, if she first fashions even a rough and ready hammer, improvised with a pointed rock fastened to the end of a stick, the striking power of her arm will be greatly amplified. The hammer augments the efficiency of her arm in three distinct ways: it transfers a greater portion of the arm's downward momentum to the nail; it amplifies the force of the arm by utilizing the principle of the lever; and it adds its own weight to the force and the weight of the arm. In a similar manner, more complex machines use a variety of devices

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[15] James and Thorpe (1994): 392-4.

to harness, transmit, guide, modify and amplify the kinetic energy of converters to perform complicated tasks.

4. *Sources of Growth in the Energy-Based Economy*

Since the standard analysis of sources of growth is based on the neoclassical production function, we need to examine how this analysis is affected by the incorporation of energy into the economy.

The neoclassical analysis of sources of growth assumes the existence of *homogeneous* labor and capital. This assumption becomes untenable in our energy-based economy, where labor performs two functions. It is a prime-mover, providing its muscular energy to production and consumption activities; and it performs a control function, directing energy flows, with or without the aid of tools, towards production and consumption activities. In any economy, the proportion in which workers combine these two functions varies from one activity to another.[16] Since economic growth reallocates labor across activities – thereby changing the proportions in which the *average* worker performs his dual functions – the nature of the labor input changes with growth. Hence, the orthodox analysis of sources of growth will only apply to a theoretical curiosity: growth without structural change.

This argument applies *a fortiori* to growth that is accompanied by a progressive switch from organic to inorganic energy. As inorganic energy – whether obtained from wind, water or fossil fuels – substitutes for the human muscle in any economy, increasingly the workers will spend their time performing control functions. This change in the roles played by workers can occur without the acquisition of new skills; with unchanged skills, the workers now spend a

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[16] In pre-industrial economies, the worker's prime-mover function was dominant in agriculture, mining, manufacturing and a variety of other activities in transportation that required hauling and heaving weights. On the other hand, the control function was more important in the services, including banking, trading, health, education, government, etc.

greater portion of their time performing control operations. As a result, even abstracting from structural change, the character of labor will change with growth. Once again, this limits the use of sources-of-growth analysis.

In the neoclassical framework, no part of economic growth is attributed to the greater use of energy. The energy – say, in the form of electricity – simply enters the national income accounts as a part of the economy's output. This treatment of energy is not persuasive. Assume an economy whose mainstay is flour milling: it employs windmills to grind imported wheat into flour. Fifty years ago, each windmill could grind only 100 pounds of wheat every day; it took one worker to operate each windmill, regardless of its speed. Over time, a slow change in climate has doubled the wind speed, so that each mill now grinds 200 pounds of wheat. What is the source of this doubling in output over fifty years? A single worker still operates each mill. Moreover, the windmills today are identical to the ones in use fifty years ago. A neoclassical economist who only looks at the unchanged inputs of labor and capital over fifty years, together with the doubling in output, will attribute all the output growth to technical change. We know better. A doubling of the kinetic energy harnessed by the windmill has produced the doubling in the output of the windmills.[17] Growth in this economy is derived solely from increased use of energy.

Consider an alternative scenario: an economy that consists of activities that employ machines powered solely by the muscular energy of workers. Assume that the value-added in any activity is directly proportional to the speed, **V**, at which these machines are operated; **V** is constrained by the amount of energy that one or more workers can apply to a machine, not by the tolerance of the machines to operation at higher speeds. In addition, we will assume that the output (or value-added), **Q**, in this economy is directly proportional to the speed of the machines, **V**. Now imagine that all the machines in this economy

[17] The results of this exercise do not change if the 'windmill' has to pay for its energy; say, it doubles its use of energy as a result of a decline in the price of this energy. At unchanged prices, this still produces a doubling in the output of the 'windmill' without any change in labor, capital or technology.

are hitched to some exosomatic source of power – say, electricity imported from a neighboring country – that raises the speed of all the machines to **2V**. We will assume that it still takes an unchanged number of workers to operate each machine; in addition, there are no changes in the capital or technology embodied in the machines.[18] On our assumption of a direct proportionality between the speed of machines and value-added, a doubling in the speed of machines also doubles the gross output to **2Q**. The growth in value-added, or net growth in output is now given by **Q – E**, where **E** is the cost of the imported electricity that now enters the economy.

What are the sources of this growth in net output, **Q** - **E**? Once again, an economist looking at the data would attribute this growth in output to technical change, since K and L have not changed. However, we know that this doubling in gross output is due to the use of energy from an exosomatic source, which allows a greater quantum of energy to be applied to each machine; we have not allowed for any change in the quantum of labor, capital or technology. It should be noted that **E** is most likely to be a fairly small part of the total output, **2Q**. The cost of **E** may be approximated by the share of the energy sector (plus net energy imports) in the economy. In the event, growth in energy use becomes a major source of economic growth.

Our narrative so far has underestimated the output growth contributed by the switch from muscle power to electricity. We have assumed that the number of workers tending a machine remains unchanged even after workers have been replaced as sources of energy. This is unrealistic. Freed from performing the function of prime-movers, each worker now has more time to devote to his control function. As a result, the machines will now engage fewer workers, thus freeing some portion of the labor force for employment in new activities. In a similar manner, whenever the economy gains access to new supplies of

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[18] The higher speed of operation of the machines is due to the ability of the exosomatic sources of power to operate steadily – without any break – and to concentrate greater amounts of energy in any one place than was attainable when workers were the only source of energy.

energy from inorganic sources, this may also free up lands for new uses. Thus, the use of coal for heating homes or cooking frees up forest lands for producing food, fiber and fodder, thereby increasing the capacity of the land to support a larger population or support an unchanged population at a higher standard of living. In short, the infusion of inorganic energy into the economy frees up both land and labor.

Perhaps more importantly, we should examine the impetus which new sources of energy – from whatever source – give to technological change.[19] Once animals were domesticated, there followed over time many innovations that harnessed animal power for work. Amongst the most important of these were innovations that led to the use of animals in plowing, drawing water from wells, driving machinery, riding, and pulling carts, carriages, barges and chariots. We encounter a similar proliferation of innovations that harnessed the power of wind- and water-mills for use in industrial processes. Once steam power became available, there flowed a series of innovations that applied steam power to a growing array of manufacturing and transportation activities. Indeed, these innovations have defined the Industrial Revolution.

5. *Two Systems of Economy*

We begin with a two-fold taxonomy of economies, based on their sources of energy: 'renewable' economies, deriving their energy primarily from renewable sources; and 'non-renewable' economies, deriving their energy primarily from non-renewable sources.[20]

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[19] Georgescu-Roegen (1975) understood this connection very well. He writes: “Now economic history confirms that great strides in technological progress have generally been touched off by a discovery of how to use a new kind of accessible energy.”

[20] There are four sources of renewable energy: the (i) sun (produces organic compounds, light, heat and winds), (ii) the sun and gravity (produce rivers), (iii) moon’s gravity (produces tides), (iv) subterranean hot water (provides heat); and four sources of non-renewable energy: (i) chemicals (produce explosives, chemical energy), (ii) fossil fuels

Although there are several possible 'renewable' economies, we will focus on one that derives most of its energy from organic matter. This ‘organic’ economy best describes the historical economies that have existed down to the first decades of the nineteenth century. Since the early 1800s, however, the organic economies have been making the transition to ‘fossil’ economies, which derive most of their energy from three fossil fuels – coal, oil and gas. The Industrial Revolution can be defined as the transition from an organic to a fossil economy.

The switch from organic to fossil fuels was accompanied by a dramatic acceleration in growth rates of national output. Over the eight centuries before 1820, the global output grew at a rate of 0.22 percent per annum; between 1820 and 1998, this growth rate increased ten-fold to 2.21 percent per annum. The average per capita income for the world economy over these two periods grew at 0.05 and 1.21 percent respectively. The world per capita income in 1998 was $5709 compared to $667 in 1820, both measured in 1990 international dollars.[21]

Neoclassical economists attribute this acceleration in growth, starting in the nineteenth century, to rising capital accumulation and technical change.[22] This explanation is constrained by what is missing from the neoclassical framework: energy. Once we recognize the centrality of energy to the economy, this forces us to think of the contribution of energy to this growth acceleration. We need to investigate if the transition from plants to fossils – as sources of energy – altered the nature of constraints on supplies of energy available to an economy.[23]

The classical economists understood quite well that sustained growth could not occur once all the land had been brought under cultivation. As the labor

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(produce heat), (iii) naturally occurring fertilizer deposits (accelerate plant growth), and (iv) uranium (produces heat).

[21] Maddison (2001): 28.

[22] In turn, these shifts are explained by the new institutional economists as the result of improvements in property rights, which created greater incentives for savings, investment and innovations. See Nathan and Birdzell (1986).

[23] For much of this discussion I will be drawing on Wrigley's (1992) pioneering analysis of the industrial revolution as a switch from organic to fossil fuels.

force grew in response to higher labor productivity and higher wages, the economy was quite capable of equipping each new worker with the additional capital. This growth in capital and labor, however, would yield diminishing returns when applied to fixed amounts of land.[24] The resulting downward pressure on wages and profits would eventually return the economy to a new stationary state at an unchanged subsistence wage but with higher *levels* of population and capital. In other words, growth in labor productivity in the classical economy was sure to return the economy to a new stationary state.

In order to make the classical economy compatible with sustained growth, we need to make one of two changes in its assumptions. We can do this by eliminating the organic economy's land constraint. In an economy with unlimited supplies of land, a growth in population, stimulated by technical change in agricultural and higher wages, will not run into the self-limiting barrier of diminishing returns to labor. As a result, each new episode of technical change in agriculture results in a permanent increase in labor productivity and wages. Technically, the assumption of unlimited supplies of land is equivalent to dropping the land constraint by converting it into capital. This was the solution adopted by the neoclassical economists.

Another trick that will prevent the return of the economy to a stationary state at the original wage is upward adjustments in subsistence wage over time. The subsistence wage can rise as workers get used to higher wages in periods of prosperity, or the impetus for this may come from the introduction of new consumption goods. Once we introduce such a mechanism, an increase in agricultural productivity will not be offset by rising rates of fertility. Instead, fertility will be adjusted downwards to balance the declining mortality rates that result from higher wages. The fact that few organic economies experienced sustained improvements in their living standards, however, points to the difficulties in establishing these preferences. Clearly, this is a subject that deserves

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[24] If land is of uneven quality, the downward pressure on marginal returns to labor (and capital) is present from the outset.

careful consideration in its own right.

Sustained growth in the classical economy will be difficult, even in the absence of Malthusian constraints, because of inherent limits on technical change in an organic economy. The potential for productivity gains from division of labor were quite limited in agriculture, a fact well-understood by Adam Smith (1776: I.1.4). Regional specialization in agriculture, to take advantage of differences in soil and climate, was also constrained by the bulkiness of agricultural output. Finally, there existed very limited opportunities for applying power from water- and wind-mills to agriculture and transportation; these sources of power could not be adapted for use in plowing, sowing, weeding or harvesting. Since division of labor is the strongest stimulant for technical change – specialization produces new and improved skills and facilitates mechanization – the weakness of this dynamic in agriculture ensured that the offsets to diminishing returns would remain weak. This nearly helped to lock the organic economy into a low subsistence wage.

The dramatic acceleration in economic growth as organic economies switched to fossil fuels are most plausibly linked to the disappearance of the earlier constraints on energy flows imposed by limited amounts of land. The technology for harnessing fossil fuels added to the organic economy a practically inexhaustible source of energy. At least for the foreseeable future, it did not matter that the stocks of fossil fuels were non-renewable; the known stocks of coal were very large relative to the rates at which they were being drawn down through much of the nineteenth century.[25] In addition, not only were

[25] Stanley Jevons (1866), a British economist of the nineteenth century, was concerned as early as 1865 about the erosion of Britain's competitive advantage as it would have to dig deeper to obtain its coal, thus raising the price of fuel. It is worth noting, however, that he was not worried about the supplies of coal being exhausted anytime soon. Indeed, in the preface to the second edition of his book, he writes: "It is almost needless to say, however, that our mines are literally inexhaustible. We cannot get to the bottom of them; and though we may some day have to pay dear for fuel, it will never be positively wanting."

new reserves of coal being discovered continually, two new forms of fossil fuels – oil and gas – would soon be added to the rapidly growing stocks of coal. As a result, the rate of exploitation of fossil fuels could rise rapidly for many more decades without raising concerns that this source of energy would be depleted anytime soon. In the early stages, the mining of coal and the steam engine were also undergoing rapid technical improvements. This meant that the energy costs of extracting these new fuels, already low, would continue to decline rapidly.[26] In other words, not only could the flows of energy from fossil fuels be expanded indefinitely, this new energy would be available at progressively lower costs with the passage of time.

Since fossil economies (in the early stages of the exploitation of the fossil fuels) have access to practically inexhaustible stocks of energy, their growth is constrained only by the rate at which this energy can be harnessed for economic activities. In other words, the growth rate of fossil economies will depend upon the amount of capital deployed (a) to extract the fossil fuels, (b) convert fossil fuels into usable forms of energy, and (c) harness this energy to produce goods and services. In other words, the magnitude of energy flows that can be channeled into economic activities in a fossil economy depends upon an endogenous factor, the rate at which the economy can accumulate capital to extract, convert and harness energy. The injection of growing flows of energy into the economy – *via* capital accumulation – creates a dynamic of cumulative growth. Capital accumulation injects energy into the economy; and this in turn, through a variety of feedbacks, produces more capital accumulation.

What are some of these feedbacks? Consider how this new dynamic affects labor productivity in agriculture. In an organic economy, agricultural productivity is limited by the amount of land; this is because the energy – in the form

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[26] The energy required for exploration and production of oil from the richest Middle Eastern oilfields amounts to a mere 0.005 percent of the energy contained in a kilogram of crude oil. Refining absorbs another 4 to 10 percent of the energy of crude oil. Smil (1994): 13.

of food, draft animals, fertilizers and pesticides – that can be applied to land is derived from the land itself. This vicious cycle is broken once agriculture can draw increasing flows of energy from an external source, *viz*. fossil fuels. The energy from fossil fuels becomes available in a variety of forms – power-driven machines, inorganic fertilizers, pesticides and water (pumped from the ground). As a result, productivity per worker in agriculture rises, allowing agriculture, for the first time, to progressively reduce its labor force while producing growing supplies of food and raw materials.

The growing diversion of labor from agriculture feeds positively, through several channels, into the virtuous circle of growth in a fossil economy. The labor released from agriculture can be combined with more energy (also from fossil fuels) to produce more and better agricultural machinery, fertilizers, pesticides, creating yet another round of growth in agriculture. Similarly, some of these workers can be employed to produce cheaper transportation; this too will create productivity gains by facilitating greater regional specialization in agriculture. Of course, some of the workers released from agriculture will be employed to process the growing supplies of food and raw materials now made available by agriculture. It is well known that growth in the scale of these processing activities, *via* greater division of labor, can produce sizable gains in productivity. Thus, the rise in agricultural productivity will stimulate productivity growth by facilitating greater division of labor in manufactures that process foods and agricultural raw materials.

The availability of cheaper energy from fossil fuels reduced the demands upon land to supply fodder, fuels and raw materials. Increasingly, as fossil fuels were used for transportation, cooking and heating, vast amounts of lands previously used for fodder and forests were diverted to growing food and fibers, thereby increasing the ability of the land to support a larger population. The energy from fossil fuels created two additional feedbacks for the economy. First, the application of this cheaper energy to mining and refining ores greatly expanded the supply of inorganic raw materials from minerals. Since the metals and cement extracted from minerals could substitute for wood in construction and machines, this too augmented the supplies of land available for growing food and fibers. At the same time, since steel is stronger, more durable, more malleable, impervious to liquids, and steel parts produce less friction, the availability of cheaper steel opened up vast new opportunities for designing better and bigger buildings, machinery, ships, tanks, and pipes for transporting liquids. Over time, the fossil fuels themselves were broken up to yield a variety of new raw materials, including fibers, rubber, plastics, fertilizers, etc. This too reduced the demands on land for raw materials, allowing it to produce yet more food and fibers.

Finally, consider how the harnessing of energy from fossil fuels provided both direct and indirect impetus to mechanization – substituting power-driven machines for humans and draft animals. This process first began with the invention of sails, windmills and watermills. Although the power harnessed by wind- and water mills found a growing range of applications in manufacturing processes in the centuries before 1800, its impact remained limited because of three constraints. These converters harnessed limited amounts of energy that were available at limited sites and in limited concentrations; in addition, mechanization was often limited by the wooden construction of the machinery. The new converters – steam engines, internal combustion engines, turbines and motors – overcame these constraints on mechanization. This has led to an unending proliferation of applications of power to bigger, faster, as well as smaller machines to substitute for the work of muscles.

The transition from an organic to a fossil-based economy was very rapid. In 1800, the global economy was overwhelmingly organic. People and animals provided 95 percent of the energy of all prime movers in 1800; this share had declined to 85 percent in 1850, 60 percent in 1900, five percent in 1950, and less than one percent in 1990. A similar switch occurred during this period in the sources of fuels. In 1850, biomass contributed 80 percent of the world's fuels; this share had dropped to 35 percent in 1900, and it was 15 percent in 1970 where it held steady for the next twenty years.[27] It has taken much less than two centuries for the developed parts of the global economy– containing one-fifth of the world's population – to switch from an organic to a fossil base.

The switch to a fossil-based economy has greatly increased the consumption of energy per capita – beating the Malthusian trap. While the availability of energy per capita increased little in the era of organic economies, the per capita consumption of energy increased at least thirteen-fold between 1850 and 1990.[28] On the other hand, the average world per capita income rose by a factor of 8.6 between 1820 and 1998. This would indicate a significant increase in the energy required to produce each dollar of output, the result no doubt of cheaper energy. It is worth noting that the dramatic increase in the availability of energy per capita was achieved despite a rapidly growing population over this period; between 1820 and 1998 world population increased by a factor of 5.7.[29]

6. *Some Concluding Remarks*

What are the differences between the economy as energy-system and the neoclassical approach to the economy as summarized in the aggregate production function?

A thumbnail sketch of the economy as an energy-system will help to bring out these differences. The economy consists of streams of energy-producing and energy-using activities; energy is central to this economy because it drives all economic activities. This focus on energy directs our attention to its sources in nature, to activities that convert and re-convert this energy, and finally to activities that use the energy to produce goods and services. In this economy, capital and labor perform supporting roles, converting, directing and amplifying energy to produce goods and services. Until the eighteenth century, all economies derived their energy primarily from organic sources. Over the past

[27] Smil (1994): 230, 233.

[28] Smil (1994): 187.

[29] Maddison (2001): 28.

two centuries, we have seen a transition from organic to inorganic sources of energy, primarily fossil fuels.

The neoclassical economists take energy out of the economy, thereby divorcing the economy from ecology or the sources of energy. This is captured in the concept of the production function, a mathematical mapping from factors – that include only capital and labor – to outputs, which depends on technology. As a result, the neoclassical economists' accounts of growth are presented in terms of the growth of capital, labor and technology. Energy plays no role in the stories they tell about growth and the sources of growth.

The absence of energy in the neoclassical framework makes it difficult to define labor and capital. We have seen how textbooks of economics offer unhelpful and inconsistent definitions of economics. This is not surprising since capital and labor play supporting roles in the economy that can only be understood in relation to energy. Together, they extract energy from natural sources, convert and reconvert them for use in economic activities, and then direct these flows of usable energy to both production and consumption of goods and services.

The absence of energy in the neoclassical production function distorts the standard analyses of growth and sources of growth. The neoclassical economist fails to recognize that in many cases, growth simply amounts to a speeding up of activities; if these activities use machines, it amounts to a speeding up of machines. This establishes a direct link between energy and growth: since speed often depends upon the use of energy. What this means is that growth in supplies of energy is an indispensable source of economic growth.

The absence of energy from the neoclassical framework, and its failure, therefore, to recognize the links between energy and growth, means that they will not explore the dynamic links between greater energy use and technical changes that are directed at harnessing growing supplies of energy. The introduction of new energy-converters – such as watermills, windmills, explosives or steam engine – created a powerful impetus for inventing devices to harness the growing and cheaper supplies of energy – substituting inorganic energy for both land and labor. The framework of the neoclassical production has not encouraged the exploration of these links.

The standard analysis of sources of growth is problematic because it assumes that labor is homogenous. We have seen that labor performs dual functions: providing energy and controlling energy flow. Since the proportion in which the *average* worker combines these functions changes with economic growth, we cannot assume that labor is a homogenous factor in the context of growth. This calls into question the analysis of sources of growth.

The neoclassical economists have also missed the significance of thinking in terms of the distinction between organic and fossil economies. Without an understanding of these different energy regimes, they failed to develop a proper appreciation of the sources, timing and speed of the economic transformations that have occurred since the early decades of the nineteenth century. Instead, they have sought to explain the Industrial Revolution in terms of technical change stimulated by scientific discoveries. Similarly, they failed to explore the manifold ways in which the lifting of constraints on energy supplies – resulting from the switch to fossil fuels – stimulated successive rounds of innovation and the growth of capital and skills. For the same reason, neoclassical economists are unlikely to look for explanations of unequal development of two economies in the different energy constraints imposed by their ecology.

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