# The Economy As An Energy System

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The standard neoclassical construct of the economy is one of the simplest yet devised by economists. Indeed, it cannot fail to impress by its tenacious adherence to the principle of Occam's razor.

Three variables define the neoclassical approach to the economy: capital, labor and goods. In this economy, production in each period begins with given amounts of capital and labor, and terminates in the production of final 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 say nothing about how labor is produced or reproduced. It enters their economy as a gift of nature.

Every economics undergraduate learns that capital and labor are 'factors' of production; in some formulations, they are described as 'means' of production. This means that the services of these two factors contribute to the production of goods and services. However, economists say very little about the specific contributions that these factors make to production.[1] The economists' definition of labor and capital are at best perfunctory. The textbooks 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 de-

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[1] One text on the history of economic thought, by Stanley Brue (2000), in its sixth edition, does not even contain an 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.

fined 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 is another anomaly. Although draft animals ranked second only to humans as prime movers in all agrarian economies before 1800 – and in some backward ones they still do – they have never been treated as a factor of production; not even by the classical economists.[2] But there is a more serious omission in the neoclassical economist's account of the economy. It fails to come to terms with the contribution of energy to the economy. Few economists have worried about this omission.

Among economists, Nicholas Georgescu-Roegen (1972, 1976) stands nearly alone in taking economics to task for this omission. He pointed out that Marxists and neoclassical economists abstract from nature; they takes resources and energy flows for granted and ignore the economy's output of wastes. This not only produces mechanistic models of the economy, in which economic processes are reversible, but it ignores the implications of entropy for economic activity and growth. Standard economics, Georgescu-Roegen (1976: 30) argues, ignores the fact 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 world view that shuts out nature from its calculus.

My objectives in this paper are three-fold. First, I offer an alternative conceptualization of the economy: one that recognizes energy as the basis of all economic activities. Second, once we recognize that the economy is an energy-system, I show that this allows us to arrive at a better

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

understanding of what people (labor) and capital do in this economy. They perform similar functions: both create and direct energy flows. Thirdly, we examine how the dynamics of an economy is affected by the nature of the sources from which it draws its energy; whether the energy is derived primarily from plants or fossil fuels. This analysis will illustrate how our focus on energy can explain two of the central facts of the history of human economies – the near stagnation in living standards in agrarian economies before 1800 and the dramatic acceleration in growth in at least a few economies since 1800.

### *Energy In The Economy*

Although energy is the driving force behind all economic activities, it never enters into the discourse of neoclassical economics. It is not even a factor of production. Instead, neoclassical economists treats energy as an intermediate good, at par with yarn, cement, timber or steel.

The classical economists too made no explicit allowance for energy in their theories of the economy. However, energy entered implicitly into their theories when they identified agriculture as a distinct activity, separate from manufacturing and trade. The distinctiveness of agriculture consisted in the fact that labor and capital in this sector worked with land, a third factor of production. Not only was this third factor of production available in fixed quantities, its quality was variable. These characteristics of land produced a tendency towards diminishing returns to capital and labor in agriculture: the returns to additional labor and capital in agriculture were progressively diminishing at the margin.[3] Classical

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

economists argued that Malthusian demographic mechanisms interact with diminishing returns in agriculture to push the economy towards a stationary state, characterized by constant levels of capital and population. The Physiocrats had a similar intuitive grasp of the distinctiveness of agriculture. They asserted that this was the only activity that produced a net product above and beyond the payments made to capital and labor.[4]

Neoclassical economists do not recognize land as an independent factor of production. Instead, they subsume it under the rubric of capital; land in nature is not productive until it is *developed* by labor and capital, until it becomes capital-as-land. Supposedly, once land has been 'developed' into capital-as-land, it loses the distinctiveness it possesses in classical economics; like other forms of capital, capital-as-land can be accumulated indefinitely. This deduction is erroneous. If the supply of land in nature is limited, this limit will be carried over to capital-as-land. Once all the land in nature has been developed, there can be no further additions to the stock of capital-as-land. The neoclassical economists' attempt to redefine land as capital does not banish its distinctiveness as a factor of production. This merely translates the previous fixed supply of land into a fixed supply of capital-as-land.

The decision to drop land from the classical trio of factors – land, labor and capital – may be explained as an adaptation of classical economics to make it compatible with sustained growth. In the classical worldview, with fixed supplies of land, all economies ended up in the stationary state, characterized by constancy in the stocks of labor and capital. The emergence of sustained growth during the nineteenth century called for changes in the classical paradigm. However, instead of recognizing that sustained growth was being fuelled by the infusion of energy from

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[4] Brue (2000): 39.

an exogenous source – fossil fuels – the neoclassical economists chose to suppress land as a factor constraining growth. They purged land from the classical framework by redefining it as capital. An economy with only two factors of production – land and labor, both capable of indefinite extension – could escape from the specter of diminishing returns. Growth could now occur indefinitely.[5]

Of course, banishing land from neoclassical economics creates its own problem. Wrigley (1992) has shown that the two-sector model of the classical economists was quite successful in capturing the essential dynamics of 'organic' economies, characterized by endemic poverty, that derived their energy from organic sources. By redefining land as capital and, therefore, dropping the two-fold division of the economy into agriculture and non-agriculture, the neoclassical economists were unable to explain the near-stagnation and endemic poverty of agrarian economies before 1800. This would now be explained by invoking cultural and institutional barriers which kept savings and capital accumulation in check.

The absence of energy from the neoclassical production function means that it is consigned to the ranks of intermediate goods: outputs that enter as inputs into the production of other intermediate and final goods. In other words, energy has no greater significance to the economy than any one of a multitude of intermediate goods, like glass, timber, iron ore and raw cotton. This will not do. Energy is different from the other intermediate goods in a fundamental way. Most intermediate goods – iron, glass, timber, plastics, fibers – do not contribute any energy to the production process; they do not perform any work. Instead, they provide the

[5] 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.

tangible substance – the raw material – from which final goods are fabricated. On the other hand, energy is expended in the *process* of fabricating these 'raw materials' into finished goods with more valuable characteristics. This means that there is a need to distinguish between raw materials that yield energy – including fossil fuels, fuel wood, fertilizers and pesticides – and those raw materials that do not yield any energy. Indeed, this distinction is fundamental, and it has important implications.

The centrality of energy in the economy becomes transparent once we recognize that an economy consists of a flow of activities. The economy consists of people at work – doing physical and mental work – most often with the aid of capital and/or land, to extract, apply, direct, modify or amplify flows of energy; the object of their work is to produce goods and services. Alternatively stated, an economy is the manifestation of energy as applied, directed, amplified and modified by the intervention of humans and capital goods. The conclusion is inescapable: the economy is an energy system. It extracts *and* applies energy to activities that produce goods and services or support consumption activities.

In order to illustrate our thesis about energy, consider the working of a windmill that grinds wheat. In the past, the mill has operated an average of eight hours a day; since the wind acts erratically, one mill-hand remains in attendance all the time to feed the wheat and collect the flour. Over the next fifty years, a slow change in climate produces more active winds, doubling the average duration over which the mill grinds wheat. This produces a doubling in the output of the windmill. What is the source of this doubling in output over fifty years? A single mill-hand still operates the mill at any time, though his idle periods have now been reduced. The capital invested in the windmill and the technology are also unchanged. However, an economist working on a time series on the inputs of labor, capital, wheat and flour, would attribute the rising output to technical change. We know better: the doubling in flour output has been produced by a doubling of the kinetic energy harnessed by the windmill.[6]

This energy system consists of two types of activities. First, there are activities that convert and re-convert energy into forms that can be used for production or consumption. In a second class of activities, people work – with or without tools – to transmit, direct, modify or amplify the energy made available by converters to produce or consume goods and services. The performance of these two functions – energy conversion and energy deployment – define the economy.

The conversion of energy takes two forms. First, there are activities that convert energy from primary sources, *viz.* heat and light from the sun, wind, running waters, plants, animals, fossil fuels and uranium. Primary conversions do not always produce energy in forms that are directly usable; the energy thus extracted may go through additional rounds of conversion before it can be applied to production or consumption. It should be noted that no chain of energy conversions, leading eventually to energy flows that can be used in production or consumption, will be undertaken unless its yield of usable energy is greater than the energy that is expended in the different stages of conversion. In other words, taken together, the system of energy conversions produce a surplus of energy for use in production and consumption activities. It follows that the energy-producing sector is the driving force behind the economy.

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[6] The results of this exercise do not change if the 'windmill' has to pay for its energy, and 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.

Once energy becomes available in usable forms it is converted into work. Using capital, people direct energy – from human and extra-human sources – to produce raw materials and intermediate and final goods. A second portion of the usable energy flows – in combination with human energy and consumption or capital goods – is employed to effect consumption, capital accumulation and conversion of energy. This completes the circular flow of energy in the economy, replenishing and adding to the energy (including human energy) and capital goods consumed in the production of goods and services.

To sum up: the economy is an energy system that passes through two stages. In its first stage, the economy produces energy; in the next stage, it directs this energy to produce goods and services. An economy's standard of living will depend – among other things – on the proportion of the labor force that is allocated to these two stages of economic activities. In turn, this proportion depends on the sources from which energy is drawn. We will explore these connections in a later section that examines the logic of organic and fossil-based economies.

### *What Do Labor And Capital Do?*

Capital and labor perform two functions in the economy: in different ways, they convert energy flows and manage – direct and manipulate – them to produce goods and services.

Two types of energy conversions occur in the economy: organic and inorganic. The first occurs through 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. The energy embodied in plants is then converted by animals into a new set of organic compounds, body heat, mental activity, and kinetic energy. In the economy, humans stand 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 them into fossil fuels, coal, oil and gas. To this chain of inorganic converters, humans have added a variety of devices – capital goods – that pick up the chain of conversions where inorganic nature leaves off. The objective of these new converters is to transform energy into forms that are usable in economic processes. For lack of a better term, we shall refer to this class of 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 – plant and animals foods – into kinetic and mental energy. Capital goods today effect a more extensive range of energy conversions. For instance, steam engines not only convert plants (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 from locations where they are available 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.[7] Windmills first appeared in what are now eastern Iran and Afghanistan in the early Islamic period, and spread to Western Europe in the twelfth century.[8] 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 electro-magnetism has produced a proliferation of converters, including electric motors, light bulbs, radio, telegraph, telephone, fax machines, television, computers, etc.

Humans perform a second economic function managing energy flows. These sentient and 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 energy efficiency. It is only quite recently, 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 their management of energy flows, humans generally use tools and machinery to direct, modify and amplify energy flows in order to perform a growing variety of complex tasks. Consider how a hammer, one

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[7] Smil (1994): 225.

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

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

It is not surprising that labor and capital do very nearly the same things; this result flows from the nature of the economy as an energy system. Once the economy is conceived as a system that uses energy to produce goods and services, it is defined by two sets of activities: (a) those that create energy flows and (b) others that direct these flows for producing goods and services. One can image a primeval economy where both functions are performed exclusively by labor: an economy where humans gather seeds in order to produce the kinetic energy for gathering seeds. In order to gather more seeds, however, labor invented tools and harnessed extra-human sources of energy to produce more seeds. As labor invents tools that allow her to harness extra-human sources of energy – initially, draft animals – she also invents tools that allow her to put the growing flows of energy to productive work. The two processes are connected.

When examined in terms of their relationship to energy flows, labor and capital are seen as working together: it is a cooperative relationship. But that is only because we have allowed labor to own all the capital so that she reaps all the fruits of capital accumulation. In this case, capital accumulation that hurts labor would never be undertaken. Once the ownership of capital is separated from labor, the relationship between the two becomes adversarial. There now emerges an enduring conflict over how the joint products of labor and capital will be shared between labor and the capitalists. Capital accumulation – in converters and tools – can now be employed to weaken the power of labor to increase her share of the output.

***Two Systems of Economy***

If the economy is an energy system, we should be able to develop a taxonomy of the economy based on the sources from which it derives its energy.

An economy may derive its energy from a variety of primary sources: including the sun (produces organic compounds, solar heat and winds), the sun and gravity (produce rivers and streams), moon's gravity (produces tides), subterranean hot water (provides heat), chemicals (produce explosives), fossil fuels (produce heat), naturally occurring fertilizer deposits (accelerate plant growth), and uranium (produces heat). The first four sources are renewable energy flows: at least in principle, they are available indefinitely. The four remaining sources are stocks of non-renewable energy; they can be depleted over time periods that will vary with the size of the original stocks and the rate of use. This suggests a two-fold taxonomy of economies based on their sources of energy. In one, the energy is obtained primarily from renewable sources; the second obtains its energy primarily from non-renewable sources. For short, we shall refer to them as renewable and non-renewable economies.

Although there are many possible 'renewable' economies – deriving their energy from renewable sources – there is one that was dominant nearly everywhere before 1800. We shall refer to this as the organic economy since it derived most of its energy from a single source, *viz*. organic matter. Since 1800, however, a growing number of economies have turned to one of three non-renewable sources for their energy: coal, oil and gas. We shall refer to them as non-renewable, fossil-based economies; for short, fossil-based economies.

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. As a result, the world per capita income in 1998 was $5709 compared to $667 in 1820, both measured in 1990 international dollars.[9]

What is the source of this dramatic acceleration in the growth rate of world output since 1800? Orthodox economists explain this acceleration in terms of higher rates of capital accumulation and technical change; in turn, these shifts are attributed to improvements in property rights which created greater incentives for savings, investment and innovations. Once we recognize the centrality of energy to economic activities, this opens up an explanation at a deeper level. We can explain the differential growth record of the periods before and after 1800 in terms of the differ-

[9] Maddison (2001): 28.

ential constraints that organic and fossil-based economies impose on the rates at which energy can be harnessed in these economies.

Economic growth in an organic economy is constrained by a relatively rigid upper limit on the availability of land. An organic economy derives its energy flows from organic matter – animals, plants and trees – which require land for their nurture. As long as unused supplies of arable lands, forests and waters (with fish) are still available, the economy can grow at least as fast as the labor force. But once these resources have been used up, growth in the labor force yields diminishing returns at the margin, exerting a downward pressure on the availability of energy per capita. If land is of uneven quality, the downward pressure on marginal returns to labor (and capital) is present from the outset. The equilibrium *level* of energy flows per capita will depend on the mechanisms that regulate the size of the population.

According to Thomas Malthus, this mechanism is quite simple. How this works is best explained by first defining the wage – the subsistence wage – at which the fertility rate (births per thousand per year) exactly offsets the mortality rate (deaths per thousand per year). When the wage is above subsistence, mortality rates decline because people have more to eat, and fertility rates rise because people marry at a younger age. Very quickly, the rising population reverses the earlier increase in living standards. In addition, with a lag, the rising labor force brings down the yield of energy per worker *via* the tendency towards diminishing returns. In the end, the economy is pushed back to subsistence, though the new equilibrium is established at a higher population. When the wage falls below subsistence, an opposite population dynamic restores it to its original level. In other words, if the economy departs from the subsistence wage for any reason, changes in fertility and mortality rates restore it to its original wage. Only the *level* of population changes as the economy makes the transition to a new equilibrium.

As long as this Malthusian mechanism remains in force, improvements in agricultural productivity can never produce sustained growth or lead to a new equilibrium at a higher subsistence wage.[10] Lower mortality, early marriages or shorter birth intervals follow inevitably upon any improvements in living standards; together, they raise the population. Instead of leading to higher living standards, productivity gains are translated into a larger population at unchanged standards of living. In order to break this vicious cycle, the relationship of fertility to the subsistence wage would have to change. There would have to occur some changes, whether economic or social, which increase the attractiveness of higher living standards enough to persuade families to delay marriages or have fewer children. Once these new preferences are firmly established, innovations in agriculture can then be translated into a higher subsistence wage. The fact that few organic economies experienced sustained improvements in their living standards points to the difficulties in establishing these preferences. Clearly, this is a subject that deserves careful consideration in its own right.

Apart from the Malthusian mechanism, growth in the organic economy was also inhibited by its limited opportunities for division of labor. Unlike, manufacturing activities and service, most agricultural operations are performed sequentially, making it impossible for workers to special-

[10] Most of them were land-saving innovations: the result of improvements in seeds, fertilizers, irrigation practices, ploughs and crop rotations, or the introduction of new crops allowing multiple-cropping. Labor-saving innovations came in the form of better harnesses for draft animals, better animal-drawn carts, and the introduction of wheel-barrows, seed drills, etc.

ize in soil preparation, planting, weeding, fertilizing, harvesting, threshing, storing or transporting agricultural output. Instead, these operations are performed sequentially by the same set of workers. As a result, agricultural expansion involves establishing new farms – when unused land is still available – that merely replicate the work of existing farms. There is some specialization on crops arising from differences in soil and climatic conditions, but this too is constrained by the high costs of land transportation due to the bulkiness of agricultural output. This meant that growth in agriculture did not generate any marked tendency towards greater division of labor. Since division of labor is a powerful stimulant for technical change – specialization produces new and improved skills and 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.

There was also a fortuitous factor that held back growth in organic economies. It is merely a matter of chance that the early yields in agriculture were universally low despite the abundance of fertile lands. Agricultural yields in colonial America, free from any land constraints, never rose too far above the levels in England. It is these low yields – and, therefore, low living standards – that produced high mortality and fertility rates, the twin pillars of the Malthusian mechanism. Had agriculture been more productive at the outset when land was abundant – so that ten agricultural workers could support, say, ten non-agricultural workers – a different demographic mechanism more supportive of growth was likely to emerge. The higher living standards would improve longevity, create a more diversified consumption, and allow more time for leisure; together, these conditions would help to increase the attractiveness of consumption over larger families. In addition, more resources could be devoted to advancing knowledge, and this could quicken the pace of technological change. All things considered, these conditions would make it more likely that gains in productivity would outstrip advances in population.

The dramatic acceleration in economic growth as organic economies switched to fossil-fuels must be attributed to disappearance of the old constraints on energy flows. 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. In addition, not only were new reserves of coal being discovered all over the world, 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 technology for mining coal as well as the technology of the steam engine were also undergoing rapid improvements. This meant that the energy costs of extracting these new fuels, already low, would continue to decline rapidly.[11] 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-based economies have access to practically inexhaustible stocks of energy, their growth is constrained only by the rate at which

[11] 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.

this energy can be harnessed for economic activities. In other words, the growth rate of fossil-based 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-based 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 multitude 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 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-based 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 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 of ores greatly expanded the supply of inorganic raw materials from minerals. Since the metals and cement extracted from minerals could substitute for wood as construction material and machinery, this too added to 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. Finally, 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 – the substitution of the work of humans and draft animals by power-driven machines. Thus defined, the connection between growing supplies of energy from inorganic sources and mechanization is tautological. 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 upon 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, 5 percent in 1950, and less than 1 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.[12] 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.

As we might expect, the switch to a fossil-based economy has greatly increased the consumption of energy per capita – beating the Malthusian trap. The availability of energy per capita varied little over time in the era of organic economies. The per capita consumption of useful energy has increased at least thirteen-fold since 1850.[13] 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 cheaper and more abundant energy has led to a lowering of overall efficiency in the uses of energy. This 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.[14]

### *Some Concluding Remarks*

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

A thumb-nail sketch of our economy as an energy-system will help to bring out these differences. This economy is an evolving and dynamic process with energy at its center, its motor force. This energy-economy consists of complex and evolving production and consumption processes,

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[12] Smil (1994): 230, 233

[13] Smil (1994): 187.

[14] Maddison (2001): 28.

which are driven by energy and energy-converters and supported by the managerial intervention of managerial hierarchies, knowledge, skills, machines and coded instructions; the managerial interventions direct and amplify the energy flowing through the energy system. At the base of this system are flows of energy, now drawn mostly from fossil fuels.

The neoclassical production function simplifies this complex, multi-layered process to a single relationship between three flows: output, capital and labor. The omission of energy from his framework means that the neoclassical economist will miss the distinction between organic and inorganic economy, a fundamental distinction without which there can no proper appreciation of the timing, speed and the magnitude of the economic transformations that have occurred since 1800. This also means that the neoclassical economist will fail to grasp how the lifting of constraints on energy supplies – imposed by a fixed amount of land in an organic economy – drove massive rounds of capital and skill accumulation. Also, the neoclassical economist is not likely to look at differences in the ways in which two organic economies were supplied with energy – say, the West European and the Middle Eastern – to explain the long-term differences in their patterns and trajectories.

There are other problems which flow from the exclusion of energy from the neoclassical framework. Without energy, it is difficult to define the true functions of labor and capital in the economy: creating and managing energy flow. This is what accounts for the superficial and inconsistent definitions of labor and capital we encounter in the standard economics texts. This is also why the neoclassical economists do not attempt to distinguish between capital as energy converters and capital as energy-using tools. The two are always lumped together as if they perform the same functions in the production process.

The neoclassical production function also freezes the economic process into a static mapping of the relations between capital and labor on the one hand and output. Even as a static description, this cannot be very helpful since this fails to account for energy: a case of missing variables.[15] This formulation also fails as a description of an agrarian economy: it does not incorporate land (available in fixed amounts) or draft animals. If the neoclassical production function is incorrectly specified, it is hard to tell what is being estimated by the endless exercises which regress output on various measures of labor and capital.

The absence of energy also skews standard measures of technical change. It is easy to see that a greater input of energy into a production system can increase its output by increasing the speed of its operations. However, within the neoclassical framework, this growth in output will be attributed to technical change. Similarly, where technical change increases the amount of energy harnessed from nature or reduces the loss of energy during production, the resulting growth in output will once again be identified as technical change. It would appear that neoclassical measures, which do not account for energy, are likely to overstate the contribution of technical change to economic growth.

Finally, the focus on energy should help to place the economy back in the matrix of nature. The economy not only draws energy from nature – as fossil fuels and agricultural products. The economy also depends on nature's vast energy system for supplies of several free or nearly-free life-sustaining conditions: water, air, sunshine, climates that sustain life,

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[15] The gross domestic product of an economy depends not only on its stock of capital, labor and stock of knowledge. It also depends on the energy that is available to the economy – to power humans, draft animals and all the energy-using machines.

and protection from harmful radiations. Once this connection to nature is established, it also becomes necessary to recognize how economic activities produces wastes which impinge on the ability of nature to continue to produce these life-sustaining conditions. The neoclassical framework produces misleading measures of economic growth when it ignores these negative feedbacks and the costs they impose on the quality of life.

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