Energy and Economic Growth

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Abstract

This article surveys the relation between energy and economic growth and more generally the role of energy in economic production. While business and financial economists pay significant attention to the impact of oil and other energy prices on economic activity, the mainstream theory of economic growth pays little or no attention to the role of energy or other natural resources in promoting or enabling economic growth. Resource and ecological economists have criticised this theory on a number of grounds, especially the implications of thermodynamics for economic production and the long-term prospects of the economy. While a fully worked out alternative model of the growth process does not seem to exist, extensive empirical work has examined the role of energy in the growth process. The principal finding is that energy used per unit of economic output has declined, but that this is to a large extent due to a shift in energy use from direct use of fossil fuels such as coal to the use of higher quality fuels, and especially electricity. When this shift in the composition of final energy use is taken into account energy use and the level of economic activity are found to be tightly coupled. When these and other trends are taken into account the prospects for further large reductions in the energy intensity of economic activity seem limited. The implications for environmental quality and economic sustainability are discussed.

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1. Introduction

This article surveys the relation between energy and economic growth and more generally the role of energy in economic production. While business and financial economists pay significant attention to the impact of oil and other energy prices on economic activity, the mainstream theory of economic growth pays little or no attention to the role of energy or other natural resources in promoting or enabling economic growth. An exception of course were the extensive discussions concerning the "productivity slowdown" following the 1970s oil crises. Resource and ecological economists have criticised this theory on a number of grounds, especially the implications of thermodynamics for economic production and the long-term prospects of the economy. While a fully worked out alternative model of the growth process does not seem to exist, extensive empirical work has examined the role of energy in the growth process. The principal finding is that energy used per unit of economic output has declined, but that this is to a large extent due to a shift in energy use from direct use of fossil fuels such as coal to the use of higher quality fuels, and especially electricity. When this shift in the composition of final energy use is taken into account energy use and the level of economic activity are found to be tightly coupled. When these and other trends are taken into account the prospects for further large reductions in the energy intensity of economic activity seem limited. These findings have important implications for environmental quality and economic and environmental policy.

This article is structured to cover these key points in a systematic fashion. The first section of the article reviews the background theory of production and growth from different points of view – those based in economics and those based in the natural sciences. The starting premise is that gaining an understanding of the role of energy in economic growth cannot be achieved without first understanding the role of energy in production. The section starts by reviewing the scientific basis of the role of energy in production and hence also in the increasing scale of production involved in economic growth. However, institutional phenomena also affect how this role plays out and therefore the economics view of growth and production and potential role of energy is necessarily more complex than just this scientific understanding. The mainstream theory of economic growth is, therefore, reviewed next. The development of both natural and especially social sciences such as economics partly reflects historical accident both in those subjects that have been considered worthy of study and the ways in which they have been studied. This is certainly true of the theory of growth and the limitations of its consideration of energy and other resource issues has been the subject of strong criticism grounded in the biophysical theory of the role of energy. A review of these alternative viewpoints completes this first section of the article.

The next section uses the mainstream economics or neoclassical concept of the production function to examine the factors that could reduce or strengthen the linkage between energy use and economic activity over time. This production theory is very general and less subject to criticism than the specific models of economic growth discussed in this article. These key factors are:

- substitution between energy and other inputs within an existing technology,
- technological change,
- shifts in the composition of the energy input, and
- shifts in the composition of economic output.

Each of these themes has a subsection dedicated to its discussion.

Up to this point all of this is theory. Numerous ideas and views exist about the potential linkages between energy and economic growth. Choice between these theories has to be on the basis of both inherent plausibility and consistency and perhaps more crucially empirical evidence. Therefore, the next section of the paper moves on to review studies that investigate the strength of the linkage between energy and growth. To be useful, such studies must not be grounded in a single theory, potential mechanism, or school of thought. Therefore, the studies reviewed here are primarily reduced form models that do not specify structural linkages between energy and output. As correlation and regression analysis does not imply causality from one variable to another, most of the these studies employ the econometric notions of Granger causality and cointegration to test the presence of and direction of causality between the variables.

The final section of the article looks at the implications of the theory and empirical results for environmental quality.

2. Theory of Production and Growth

This section starts by reviewing the scientific basis of the role of energy in production and hence also in the increasing scale of production involved in economic growth. However, institutional phenomena also affect how this role plays out and therefore the economics view of growth and production and potential role of energy is necessarily more complex than just this scientific understanding. The mainstream theory of economic growth is, therefore, reviewed next. The development of both natural and especially social sciences such as economics partly reflects historical accident both in those subjects that have been considered worthy of study and the ways in which they have been studied. This is certainly true of the theory of growth and the limitations of its consideration of energy and other resource issues has been the subject of strong criticism grounded in the biophysical theory of the role of energy. A review of these alternative viewpoints completes this section of the article.

a. Energy in Production: Physical Theory and Economic Models

Reproducibility is a key concept in the economics of production. Some inputs to production are non-reproducible, while others can be manufactured at a cost within the economic production system. Primary factors of production are inputs, which exist at the beginning of the period under consideration and are not directly used up in production (though they can be degraded and can be added to), while intermediate inputs are those created during the production period under consideration and are used up entirely in production. There is obviously some fuzziness in these definitions. Mainstream economists usually think, of capital, labor, and land as the primary factors of production, while goods such fuels and materials are intermediate inputs. The prices paid for all the different inputs are seen as eventually being payments to the owners of the primary inputs for the services provided directly or embodied in the produced intermediate inputs (Stern, 1999).

This approach has led to a focus in the theory of growth on the primary inputs, and in particular, capital and land, and a much lesser and somewhat indirect treatment of the role of energy in the growth process. The primary energy inputs are stock resources such as oil deposits. But these are not given an explicit role in the standard growth theories which focus on labor and capital Therefore, the ideas about the role of energy in the mainstream theory of growth tend to be fairly convoluted.

However, capital, labor, and in the longer term even natural resources, are reproducible factors of production, while energy is a nonreproducible factor of production though of course energy vectors - fuels - are reproducible factors (Stern, 1999). Therefore, natural scientists and some ecological economists have placed a very heavy emphasis on the role of energy and its availability in the economic production and growth processes.

The first law of thermodynamics (the conservation law) implies the mass-balance principle (Ayres and Kneese, 1969). In order to obtain a given material output greater or equal quantities of matter must enter the production process as inputs with the residual as a pollutant or waste product. Therefore, there are minimal material input requirements for any production process producing material outputs. The second law of thermodynamics (the efficiency law) implies that a minimum quantity of energy is required to carry out the transformation of matter. Therefore there must be limits to the substitution of other factors of production for energy. All economic processes require energy, though some service activities may not require the direct processing of materials. However, this is only true at the micro-level and at the macro-level all economic processes require the indirect use of materials, in either the maintenance of labor or the production of capital.

Energy is also an essential factor of production (Stern, 1997). All production involves the transformation or movement of matter in some way and all such transformations require energy. Some aspects of organized matter - that is information - might also be considered to be non-reproducible inputs. Several analysts (e.g. Spreng, 1993; Chen, 1994; Stern, 1994; Ruth, 1995) argue that information is a fundamentally nonreproducible factor of production in the same way as energy, and that ecological economics must pay as much consideration to information and its accumulation as knowledge as it pays to energy. Energy is necessary to extract information from the environment while energy cannot be made active use of without information and possibly accumulated knowledge.[1] Unlike energy, information and knowledge cannot be easily quantified. But these latter factors of production must be incorporated into machines, workers, and materials in order to be made useful. This provides a biophysical justification for treating capital, labor etc. as factors of production. Though

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[1] Obviously energy can provide uncontrolled heating, lighting etc. without any activity on the part of economic agents. But even non-intelligent organisms need to use information to make controlled use of energy. For example, when plants use some sunlight for photosynthesis rather than just heating and lighting their leaves they are using the information in their genetic code to produce chlorophyll and construct chloroplasts.

capital and labor are easier to measure than information and knowledge, their measurement is, still, very imperfect compared to that of energy (Stern, 1999).

In the mainstream neoclassical economics approach, discussed below, the quantity of energy available to the economy in any period is endogenous, though restricted by biophysical constraints such as the pressure in oil reservoirs and economic constraints such as the amount of installed extraction, refining, and generating capacity, and the possible speeds and efficiencies with which these processes can proceed (Stern, 1999). Nevertheless, this analytical approach leads to a downplaying of the role of energy as a driver of economic growth and production.

Some alternative, biophysical models of the economy propose that energy is the only primary factor of production. This could be understood as there being a given stock of energy which is degraded (but due to the law of the conservation of energy not used up) in the process of providing services to the economy. But this means that the available energy in each period needs to be exogenously determined (Stern, 1999). In some biophysical models (e.g. Gever *et al*., 1986) geological constraints fix the rate of energy extraction. Capital, and labor are treated as flows of capital consumption and labor services rather than as stocks. These flows are computed in terms of the embodied energy use associated with them. The entire value added [2] in the economy is regarded as the rent accruing to the energy used in the economy. An alternative to the neoclassical marginal productivity distribution theory is therefore necessary (e.g. Kaufmann, 1987). As in Marxist economics, the actual distribution of the surplus depends on the relative bargaining power of the different social classes (Kaufmann,

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[2] Costanza (1980) views net output of the economy as gross fixed capital formation, inventory change, and net exports. This is equal to net saving. In the latter view, the goal of the system is growth and all energy used by labor in current consumption is necessary to fund its productive activity. In the model underlying Hall *et al*. (1986), Gever *et al.* (1986), or Kaufmann (1987), only part of the energy used by workers is necessary for subsistence that enables them to perform their economic role. The remainder is surplus which increases their utility but does not increase their productivity (Hall et al. (1986, 107-108). The value of net output which is bargained for by domestic social classes is therefore conventional GDP minus a subsistence level of income. This is consistent with the classical economic model.

1987; Hall *et al*., 1986) and foreign suppliers of fuel.[3] Energy surplus is appropriated by the owners of labor, capital, and land. The Leontief input-output model represents an economy in which there is a single primary factor of production with prices that are not determined by marginal productivity. Marginal products are zero but there is a vector of positive equilibrium prices. There is a single fixed proportions technique of production for each commodity in terms of the flows of commodities or services required (Stern, 1999). This representation of the economy or an ecosystem with energy as the primary factor was proposed by Hannon (1973a).

These ecological economists argue that the energy used to produce intermediate resource inputs such as fuels increases as the quality of resources such as oil reservoirs declines so that rising energy cost represents an increase in scarcity in the use value sense (Cleveland and Stern, 1999).

There might seem to be a paradox between the treatment of energy as the only primary factor and a concern about the quality of other resources. Changing resource quality is treated in the model as changes in the input-output coefficients i.e. a form of technical change. In the Costanza approach and the emergy approach (see Brown and Herendeen, 1996) resources are represented by their embodied solar and geological energy. Thus changing resource quality is represented by changes in the embodied energy of the resources rather than by changes in the input-output coefficients. If resource stocks were explicitly represented, energy would no longer be the only primary factor of production. The neo-Ricardian models developed by Perrings (1987) and O'Connor (1993), like all other neo-Ricardian models, have a fixed proportions technology in terms of capital stocks instead of the flows in the Leontief model. They do not distinguish between primary and intermediate factors of production. Yet that approach can still take biophysical constraints such as mass balance (Perrings and O'Connor) and energy conservation (O'Connor) into account (Stern, 1999).

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[3] Others argue that prices should be determined on the basis of energy cost (Hannon, 1973b) - a normative energy theory of value - or that prices are actually correlated with energy cost (Costanza, 1980) - a positive energy theory of value (Common, 1995). Costanza's view is that costs are determined by energy costs - an energy theory of costs. Actual prices may or may not be equal to those costs for a variety of reasons. But these authors do not provide an

If the economy can be represented as an input-output model where there is no substitution between factors of production, the embodied knowledge in factors of production can be ignored. This does not mean that the energy used to acquire and maintain that knowledge should be ignored. An accurate accounting for all energy used to support final production is important. But the contribution of knowledge to production cannot be assumed to be proportional to its energy cost. Though thermodynamics places constraints on substitution, the actual degree of substitutability among capital stocks embodying knowledge and energy is an empirical question.

b. The Mainstream Theory of Growth

As explained above there is an inbuilt bias in mainstream production and growth theory to downplay the role of resources in the economy, though there is nothing inherent in economics that restricts the potential role of resources in the economy. The basic model of economic growth is the Nobel-prize winning work by Solow (1956) that does not include resources at all. This model subsequently was extended with nonrenewable resources, renewable resources, and some waste assimilation services (for surveys see Kamien and Schwartz, 1982; Toman et al., 1994). These extended models are, however, only applied in the context of debates about environmental sustainability, not in standard macro-economic applications.

i. The Basic Growth Model

Economic growth models examine the evolution of a hypothetical economy over time as the quantities and/or the qualities of various inputs into the production process change. Here we describe the most simple model based on the work of Solow (1956). In this model a constant-sized labor force using manufactured capital produces output, which is equal to the national income. The neoclassical model assumes that output increases at a decreasing rate as the amount of capital employed rises. The uppermost curve in Figure 1 shows this relationship between output (Y) and capital (K).

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explanation of why prices will gravitate towards the embodied energy cost in an actual economy.

Now suppose that the population, assumed to be some constant multiple of the labor force, saves a constant proportion of its income. Savings are used to build new capital goods. A constant proportion of the existing capital stock depreciates (and becomes productively useless) in each period of time.

The capital stock is in equilibrium (and so unchanging in size) when saving equals depreciation. This is also shown in Figure 1. Note that the savings curve has the same shape as the output curve, but is lower for every value of K. This is because savings are a constant proportion, s, of income. The dynamics implied by Figure 1 are very simple. To the left of K^*, where capital per worker is scarce, capital investment generates a relatively large increase in future income, and so will offer a high rate of return. Moreover, it is clear from the relative positions of the S and D curves to the left of K^* that the addition to the capital stock (S) is greater than depreciation (D) and so capital rises.

However, diminishing returns to capital (shown by the decreasing rate of increase of the output curve) imply that successive increments of capital generate decreasing additions to future income, and so a falling rate of return on investment. Hence the incentive to accumulate capital weakens. When the capital stock has reached K^*, it will be at a stationary, or equilibrium, state. Additions to capital due to saving are exactly offset by reductions in capital from depreciation and the rate of return on investment will have fallen to a point at which there is no incentive to accumulate more capital.

This simple economy must sooner or later reach a stationary state in which there is no net (additional) investment and economic growth must eventually halt. In a transition process, while a country is moving towards this stationary state, growth can and will occur. An underdeveloped economy, with a small capital stock per worker, can achieve fast growth while it is building up its capital stock. But all economies will eventually settle into a zero growth equilibrium if the savings rate remains constant. No country can grow in perpetuity merely by accumulating capital.

If the labor force were to grow at a fixed rate over time, the total capital stock and the total quantity of output will rise but capital per worker and output per worker will remain constant once an economy has developed to its equilibrium. The only adjustment necessary to Figure 1 is that all units are now measured in *per capita* terms.

According to neoclassical growth theory, the only cause of continuing economic growth is technological progress. As the level of technological knowledge rises, the functional relationship between productive inputs and output changes. Greater quantities or better qualities of output can be produced from the same quantity of inputs. In the simple model we are examining, technological progress continually shifts the output function upwards, and so raises the equilibrium *per capita* capital stock and output levels. Intuitively, increases in the state of technological knowledge raise the rate of return to capital, thereby offsetting the diminishing returns to capital that would otherwise apply a brake to growth.

ii. Endogenous Technological Change

The simple model that we just described does not explain how improvements in technology come about. They are just assumed to happen exogenously, so that this model is said to have exogenous technological change. More recent models attempt to endogenize technological change - explaining technological progress within the growth model as the outcome of decisions taken by firms and individuals.

In endogenous growth models the relationship between capital and output can be written in the form $Y = AK$. Capital, K, is defined more broadly than in the neoclassical model. It is a composite of manufactured and knowledge-based capital. Endogenous growth theorists have been able to show that, under reasonable assumptions, the A term in the expression above is a constant, and so growth can continue indefinitely as capital is accumulated.

The key point is that technological knowledge can be thought of as a form of capital. It is accumulated through research and development (R&D) and other knowledge creating processes. Technological knowledge has two special properties. First it is a public good: the stock of this form of capital is not depleted with use. This is important as it implies that the knowledge stock can be stored over time, even when it is being used. Second, it generates positive externalities in production: whilst the firm doing R&D obtains benefits from the knowledge acquired, others benefit too - the benefits that the firm accrues when it learns and innovates are only partly appropriated by itself. There are beneficial spillovers to the economy from the R&D process so that the social benefits of innovation exceed the private benefits to the original innovator.

These externalities create momentum in the growth process. As firms install new capital, this tends to be associated with process and product innovations. The incentive to devote resources to innovation comes from the prospect of temporary monopoly profits for successful innovations. The growth of K thus means the growth of a composite stock of capital and disembodied technological knowledge. Therefore, output is able to rise as a constant proportion (A) of the composite capital stock, and is not subject to the diminishing returns shown in Figure 1.

So in an endogenous growth model, the economy can sustain a constant growth rate in which the diminishing returns to manufactured capital are exactly offset by the technological growth external effect that we described earlier. The growth rate is permanently influenced by the savings rate; a higher savings rate increases the economy's growth rate, not merely its equilibrium level of income.

So far there has been relatively little work including these approaches in models that also examine the roles of resources in growth. See the survey by Smulders (1999) for references.

iii Growth Models with Natural Resources

The growth models we have examined do not include any natural resources including energy. All natural resources exist in finite quantities though some such as sunlight or deuterium are available in very large quantities. Some environmental resources are non-reproducible; and many renewable resources are potentially exhaustible. Finiteness and exhaustibility of resources make the notion of indefinite economic growth problematic. Even sustainable development - i.e. at least no decline in output - may not be feasible.

When there is more than one input – both capital and natural resources - there are many alternative paths that economic growth can take. The path taken is determined by the institutional arrangements that are assumed. Analysts have looked at both optimal growth models which attempt to either maximization the sum of discounted social welfare over some relevant time horizon (often an infinite horizon) or achieve sustainability (non-declining social welfare) and models intended to represent real economies assuming perfectly competitive markets or other arrangements.

The neoclassical literature on growth and resources centers on what conditions permit continuing growth, or at least non-declining consumption or utility. We use the short-hand "sustainability" to refer to either continuing growth or non-declining consumption. Technical and institutional conditions determine whether or not sustainability is possible. Technical conditions refer to things such as the mix of renewable and nonrenewable resources, the initial endowments of capital and natural resources, and the ease of substitution among inputs. The institutional setting includes things such as market structure (competition versus central planning), the system of property rights (private versus common property), and the system of values towards future generations.

Solow (1974) showed that sustainability was achievable in a model with a finite and nonrenewable natural resource with no extraction costs and non-depreciating capital which was produced using capital and the natural resource. However, the same model economy under competition results in exhaustion of the resource and consumption and social welfare eventually falling to zero (Stiglitz, 1974). Dasgupta and Heal (1979) show that with any constant discount rate the so-called optimal growth path also leads to eventual depletion of the natural resource and the collapse of the economy

A common interpretation of standard growth theory is that substitution and technical change can effectively de-couple economic growth from resources and environmental services. Depleted resources or degraded environmental services can be replaced by more abundant substitutes, or by “equivalent” forms of human-made capital (people, machines, factories, etc.). But this is a misinterpretation. Neoclassical economists are primarily interested in what institutional arrangements, and not what technical arrangements, will lead to sustainability, so that they typically assume *a priori* that sustainability is technically feasible and then investigate what institutional arrangements might lead to sustainability if it is technically feasible. There is, however, a relatively unexamined assumption that sustainability is likely to be technically unless proved otherwise.

The elasticity of substitution (σ) between what economists call capital (factories, machines, etc.) and inputs from the environment (natural resources, waste assimilation, ecosystem services) is a critical technical term that indicates by how much one of the inputs must be increased to maintain the same level of production when the use of the other input is reduced. A large σ implies that the cost impact due to the rising price of one input, say natural resources, can easily be escaped by switching to a different technique of production that favors the use of another input, say capital. Figure 2 shows the different combinations of the two inputs that can produce a given level of output for different values of σ. Different levels of output were chosen for the three values of σ to make the figure clearer by avoiding the graphs crossing over.

The marginal product is the additional contribution to production of using one more unit of an input holding the levels of the other inputs constant (i.e the partial derivative of the production function with respect to that input). A unitary elasticity of substitution ($\sigma=1$), referred to as "perfect substitutability," means that as the ratio of the two inputs is changed by a given percentage holding output constant, the ratio of their marginal products changes by the same percentage (in the opposite direction)**.** This relation is shown by the curve (known as an isoquant) in Figure 2, which is asymptotic to both axes. As resource use falls towards zero, production can be maintained by increasing capital use towards infinity. It is also implied that the total cost of production is constant along the isoquant. Perfect substitutability does not mean that resources and capital are equivalently useful - in fact as resource availability declines its marginal productivity rises *ad infinitum*. The Figure also illustrates the cases where no substitution is possible and ($\sigma=0$) and where the two inputs are infinitely substitutable. In the former case the two inputs must be used in a fixed ratio and in latter case producers see no difference between the two inputs and use the cheapest one. As we discuss below, perfect substitutability is an unrealistic assumption from a biophysical perspective at least if it is assumed to apply at all possible ratios of capital and resources. Demand elasticities for energy, which in theory are related to the elasticity of substitution also indicate that the elasticities of substitution between energy and other inputs and among different fuels may be between zero and one. Furthermore, if the elasticity of substiution is greater than one then the isoquants cross the axes and inputs are nonessential for production and vice versa.

Economists such as Solow (1974) explicitly dispose of cases where σ for non-renewable resources and capital is greater or less than unity. In the former case substitution possibilities are large and therefore the possibility of non-sustainability is not an issue. In the latter case, sustainability is not feasible if an economy uses only non-renewable resources. Of course, where there are renewable resources sustainability is technically feasible, at least in the absence of population growth.

Neoclassical economists argue that the class of growth models that include resources can account for mass balance and thermodynamic constraints with the “essentiality condition.” If σ is greater than one, then resources are "non-essential." If σ is less than or equal to one, than resources are "essential." Essential in this case means that given positive non-resource inputs, output is only zero when the resource input is zero, and strictly positive otherwise. The Cobb-Douglas production function, a frequent form used in growth models, has the essentiality condition. Economists argue that this at least accounts for the fact that *some* amount of energy and materials are required to produce goods and services. But when the elasticity of substitution is unity this “essential” amount can be infintesimal if sufficient manufactured capital is applied. Economists also note that resources and capital are interdependent in the neoclassical models in that some positive quantity of resources is required to produce capital assets. Thus, the capital stock cannot be increased without depleting the resource stock. Some economists acknowledge that an assumed value for σ of one or greater between energy and other inputs violates the laws of thermodynamics (Dasgupta and Heal, 1979, p.211).

Substitution that is technically possible will not occur unless society invests in sufficient capital over time to replace the depleted natural resources and ecosystem services. How much investment does take place depends on the institutional setting of the economy. For example, in an economy where sustainability is just technically feasible (σ=1) and there are only non-renewable resources, sustainability will not occur in either a competitive or centrally-planned economy where the decision rule is the maximization of the discounted flow of utility of future generations using a constant and positive discount rate. Consumption per capita will eventually decline to zero after an initial period of economic growth because resources and ecosystem services are depleted faster than capital can be accumulated to replace them (Stiglitz, 1974; Dasgupta and Heal, 1979). Sustainability is achieved under certain institutional settings (Solow, 1974). If the utility of individuals is given equal weight without regard to when they happen to live and the aim is to maximize the sum of utilities over time, then growth in consumption can occur indefinitely. This is equivalent to maximizing net present value with a zero discount rate. Obviously, therefore, a constant level of consumption over time also is feasible. An important result in this context is the Hartwick rule (Hartwick, 1977) which shows that if sustainability is technically feasible, a constant level of consumption can be achieved by reinvesting resource rents in other forms of capital, which in turn can substitute for resources. Dixit et al. (1980) extended the rule to multiple capital stocks while Hartwick (1995) extended the rule to open economies.

The other key factor permitting in growth in the face of a limited resource base is technological change. A technological improvement is defined as a gain in total factor productivity which implies that output increases while a weighted sum of the inputs to production is held constant.

c. Critique and Alternative Views

Many ecological economists have a fundamentally different "pre-analytic vision" of the economic process than that presented in neoclassical economics. Mainstream growth theory focuses on institutional limits to growth. When economists such as Solow have addressed the technical limits to growth they tend to not take these very seriously (Solow, 1978, 1993, 1997). Ecological economists tend instead to focus on the material basis of the economy. The criticism of growth theory focuses on limits to substitution and limits to technological progress as ways of mitigating the scarcity of resources. There are two aspects to this. The first is getting more production out of a limited resource input and the second is the limited capacity of natural environments to absorb the impacts of energy and resource use. Substitution of manufactured capital and technological change could potentially reduce the significance of both issues. In this section I present the critical arguments. Empirical evidence on the significance of these arguments is discussed in the third and fourth sections of this article.

i. Limits to Substitution

There are both more than one type of substitution of inputs and more than one reason why substitution may be limited.

There can be substitution *within* a category of similar production inputs – for example between different fuels - and *between* different categories of inputs – for example between energy and machines. There is also a distinction to be made between substitution at the micro level - for example in a single engineering process or in a single firm – and at the macro level – in the economy as a whole. Additionally, some types of substitution are possible in a single country, which are not possible globally.

Solow (1997) argues that the first type of substitution (within category), and in particular the substitution of renewable for nonrenewable resources, is most important. There is no doubt that this type of substitution has played a powerful role in shaping the pattern of natural resource use in economies. The long run pattern of energy use in industrial economies is dominated by the substitutions from wood to coal, oil, natural gas and primary electricity (Hall *et al*., 1986). It is possible that the elasticity of substitution for within category types of substitution exceeds unity. This would imply that some particular inputs are nonessential.

However, ecological economists emphasize the importance of limits to the other type of substitution, and in particular, the substitution of manufactured capital for natural capital. Natural capital is needed both for energy capture and for absorbing the impacts of energy and resource use – the sink function. Even if smaller amounts of energy were needed for production, all productive activity – being a work process transforming materials using energy – will disrupt the natural environment. Often one form of environmental disruption - for example pollution – is replaced by another form of environmental disruption – for example hydroelectric dams.

Potential reasons for limited substitutability are discussed in the following:

<u>Thermodynamic Limits to Substitution</u>

Thermodynamics limits to substitution are easily identified for individual processes by an energy-materials analysis that defines the fundamental limitations of transforming materials into different thermodynamic states and on the use of energy to achieve that transformation (Ruth 1993; Islam, 1985). These types of analyses have shown where technological improvements exhibit strong diminishing returns due to thermodynamic limits, and where there is substantial room for improvements in the efficiency of energy and material use. For example, the thermal efficiency of power plants has been relatively constant for many years, reflecting the fact that it is approaching the thermodynamic limit.

Complementarity Limits Substitution

Production is a work process that uses energy to transform materials into goods and services (Cleveland et al., 1984). Georgescu-Roegen's (1976) fund-flow model describes production as a transformation process in which a flow of materials, energy, and information is transformed by two agents of transformation, human labor and manufactured capital. The flow of energy, materials and services from natural capital is what is being transformed,, while manufactured capital effects the transformation. Thus, some ecological economists argue that, for example, adding to the stock of pulp mills does not produce an increase in pulp unless there also is the wood fiber to feed them (Daly, 1991). The latter is essential an argument about material balance.

Mainstream economists think about this question differently. First they argue that though additional capital cannot conjure wood fibers out of a vacuum more capital can be used with each amount of wood fibers to produce more sophisticated and valuable products from them and that this is the relevant substitution between capital and resources. In the energy industries more capital can extract more oil from a petroleum reservoir and downstream extract more useful work in cleaner ways, only subject to thermodynamic limits. Even thermodynamic limits only apply to production of physical product. There is no limit in their view to the potential value of product created through sophisticated manipulation using larger amounts of capital.

Physical Interdependence and Macroeconomic Limits Substitution

The construction, operation, and maintenance of tools, machines, and factories require a flow of materials, energy from natural capital. Similarly, the humans that direct manufactured capital consume energy and materials (i.e., food and water). Thus, producing more of the "substitute," i.e. manufactured capital, requires more of the thing that it is supposed to substitute for.

Ecological economists argue that production functions used in growth models do not account for this interdependence, and thus assume a degree of substitutability that does not exist (Georgescu-Roegen, 1979; Cleveland et al., 1984; Ayres and Nair, 1984; Kaufmann, 1992; Daly, 1997, Stern, 1997). But both environmental and ecological economics have erred by not distinguishing among the micro-and macro-applications of production functions. Substitution is fundamentally more constrained at the macro- level of analysis than at the micro-level (Stern, 1997). For example, home insulation directly substitutes for heating fuel, a clear substitution of manufactured capital for natural capital *within the household sector.* But interdependence means that insulation requires fuel to manufacture, so for the economy as a whole the net substitution of insulation for fuel is less than that indicated by an analysis of the household sector in isolation from the rest of the economy. Put another way, the aggregate of potential savings at the macroeconomic level is less than the sum of the savings one would calculate by adding the savings from sectoral-level analyses that do not account for the indirect costs.

In Figure 3 the curve E = f(M) is a neoclassical isoquant for a constant level of output, where E is energy, and M materials. For simplicity, the diagram unrealistically assumes that no materials are required in the extraction or capture of energy. The indirect energy costs of materials are represented by g(K). Addition of direct and indirect energy costs results in the "net" isoquant E = h(K) (Stern, 1994). Generalizing for material costs to energy extraction appears to indicate that there are eventually decreasing returns to all factors at the macro level and therefore the socially efficient region of the aggregate production function does not include areas with extreme factor ratios.

At a global level, a country such as Kuwait or Nauru can deplete its natural resources and invest in manufactured capital offshore through the financial markets. But this route to substituting manufactured capital for natural capital is clearly not possible for the world as a whole.

Critical Natural Capital Limits Substitution

Ecological economists have also argued that at the macro-level some forms of "natural capital" are not replaceable by produced capital, at least beyond certain minimum stock sizes (Costanza and Daly, 1992; Pearce *et al*., 1989). These stocks may provide life-support services to the economy or represent pools of irreplaceable genetic information or "biodiversity". The limited substitutability argument has also been extended to incorporate non-linear dynamics and irreversible changes. The fear is that excessive substitution of human-made capitals for natural capital will cause the system to approach a threshold beyond which natural systems will lose resilience and suffer catastrophic collapse (Common and Perrings, 1992; Pearce and Perrings, 1994; Perrings, 1995). These propositions are not as fundamental as those based on thermodynamics and are largely an empirical question. Though we cannot demonstrate these forms of non-substitutability from basic physical laws they may be just as important as thermodynamics in constraining actual production functions.

In the energy context this argument is most relevant regarding the sink function of the environment. Using more and more of the environment as a sink for pollution means less and less of it is available for other life support uses. Alternative energy sources may require larger areas of the environment for energy capture than current fossil fuel technologies and will themselves generate wastes etc. in the production of the energy capture and transmission capitals.

ii. Limits to Technological Change

Along with substitution, the second important factor mitigating resource scarcity in the standard growth model is technological change. Even if substitution possibilities are limited, sustainability is possible if technological change is natural capital-augmenting and unlimited in scope.

The arguments for technological change as a solution would be more convincing if technological change were really something different from substitution. This is not the case. While the neoclassical model treats technological change and substitution as two separate phenomena other approaches do not. For instance, the neo-Ricardian approach (e.g. Perrings, 1987) assumes that only one technique of production is available at any one time. Any change in that technique is a change in technology. The neoclassical approach assumes that an infinite number of efficient techniques coexist at any one point in time. Changes in technology occur when new more efficient techniques are developed. However, in a sense these new techniques represent the substitution of knowledge for the other factors of production. The knowledge is embodied in improved capital goods and more skilled workers and managers, all of which require energy, materials, and ecosystem services to produce and maintain. Thus, however sophisticated the workers and machinery become, there are still thermodynamic restrictions on the extent to which energy and material flows can be reduced. There also are ecosystem properties that limit the extent to which their services can be appropriated without irreversible negative impacts.

Another question is whether technology will follow the “right” direction (Gutés, 1996). If natural resources are not priced correctly due to market failure – a common and pervasive phenomenon which is the main topic of study of mainstream environmental economics – then there will be insufficient incentives to develop technologies that reduce resource and energy use. Instead technological change would result in more resource use, not less.

Another reason to temper our technological optimism is that new technologies often are double-edged sword in terms of their overall effect on natural capital. New technologies that mitigate the scarcity of nonrenewable resources, for example, may release greater quantities or more harmful types of wastes, and hence have greater impact on renewable natural capital and ecosystem services. A defining characteristic of technical change since the Industrial Revolution is a shift from renewable to nonrenewable resources, especially fossil fuels. The use of fossil fuel-based technologies has greatly improved the productivity of renewable resources such as agriculture, forestry, and fisheries. But fossil fuel-based technologies have not improved or even maintained the productive capacity of the ecosystems that generate the crops, timber, and fish. On the contrary, society faces widespread soil degradation, deforestation, and over-exploitation of fish stocks. Pollution from the use of fossil fuels and metals in extraction, production, and consumption further deteriorates the productive capacity of ecosystems.

3. Factors Affecting the Linkage Between Energy and Growth

There has been extensive debate concerning the trend in energy efficiency in the developed economies, especially since the two oil price shocks of the 1970s. Taking the example of the US economy, energy consumption hardly changed in the period 1973 to 1991 (Figure 4). This was despite a significant increase in GDP. These facts are indisputable. What has been the subject of argument is what were the reasons for the break in the trend. It is commonly asserted that there has been a decoupling of economic output and resources, which implies that the limits to growth are no longer as restricting as in the past. This was one of the messages of the 1992 World Development Report that addressed environmental issues prior to the 1992 Earth Summit in Rio de Janeiro. (IBRD, 1992). See also the discussions in de Bruyn amd Opschoor (1997) and Bohi (1989).

This section of the article starts from the neoclassical perspective of the production function to examine the factors that could reduce or strengthen the linkage between energy use and economic activity over time. A general production function can be represented as:

$$(Q_1,\ldots,Q_m)' = f(A, X_1,\ldots,X_n, E_1,\ldots,E_p) \qquad (1)$$

where the Q_i are various outputs, such as manufactured goods and services, the X_i are various inputs such as capital, labor etc., the E_i are different energy inputs: coal, oil, etc. and A is the state of technology as defined by the total factor productivity indicator. The relationship between energy and an aggregate of output such as gross domestic product can then be affected by:

– substitution between energy and other inputs

– technological change - a change in A.

– shifts in the composition of the energy input.

– shifts in the composition of output.

Also, shifts in the mix of the other inputs – for example to a more capital intensive economy from a more labor intensive economy – can affect the relationship between energy and and output but this issue has not been extensively discussed in the literature and so will not be pursued further here. It is also possible for the input variables to affect total factor productivity though in models which invoke exogenous technological change this is assumed not to occur. This possibility is discussed in the subsection on technological change below.

a. Energy and Capital: Substitution and Complementarity

Empirical analyses of the substitution issue are few in number and varied in their results. Some suggest that manufactured capital is a good substitute for major metals (Brown and Field, 1979); others find a wide range of substitutability between manufactured capital and aggregate material inputs that is highly dependent on a prior model specification (Moroney and Trapeni, 1981); others find little or zero possibility for substitution between manufactured capital and specific strategic metals (Deadman and Turner, 1988). As Stern (1997) observes, econometric studies employing the translog and other functional forms have come to varying conclusions regarding whether capital and energy are complements or substitutes (Berndt and Wood, 1979; Apostolakis, 1990). On the whole it seems that capital and energy act more as substitutes in the long-run and more as complements in the short run, and that they may be gross substitutes but net complements (Apostolakis, 1990). Most of these are industry level elasticities, and most cover only major nonrenewable resources such as metals or fossil fuels. There are no empirical estimates of the degree of substitution between manufactured capital and any major ecosystem service.

Kaufmann and Azary-Lee (1991) demonstrate the importance of accounting for the physical interdependency between manufactured and natural capital. They use a standard production function to account for the indirect energy used elsewhere in the economy to produce the capital substituted for fuel in the U.S. forest products sector. They found that from 1958 to 1984 the indirect energy costs of capital offset a significant fraction of the direct fuel savings. In some years, the indirect energy costs of capital are greater than the direct fuel savings. The results of Kaufmann and Azary-Lee's analysis are consistent with the arguments made above that scale is critical in assessing substitution possibilities. In this case, the assessment of substitution at one scale (the individual sector) overestimates the energy savings at a larger scale (the entire economy).

The physical interdependency between manufactured capital and natural capital may limit the ability of the economy to insulate economic well-being from depletion and degradation. Kaufmann (1995) modifies a standard neoclassical growth model (Solow, 1970) to include an "environmental life support multiplier," which is the quantity of capital and labor required to produce a unit of economic output for a given level of technology. A reduction in the value of the multiplier, corresponding to depletion or degradation, implies an increase in the quantity of capital and labor required to produce a unit of economic output. Kaufmann accounts for the physical interdependency between manufactured capital and natural capital with a two-sector model in which the extractive sector uses capital and labor to produce the materials used in the rest of the economy, which in turn use those materials produce that capital and labor, as well as other consumption and investment goods. Over a broad range of plausible substitution possibilities, Kaufmann finds that any reduction in environmental life support lowers the long-run growth path of the economy. Degradation or depletion diverts more capital and labor to the extractive sector, reducing investment and/or consumption in the rest of the economy.

b. Innovation and Energy Efficiency

Berndt (1990) looks at the various mechanisms through which energy use can affect TFP growth. The Schurr hypothesis argued that innovations that allowed the use of energy sources such as electricity were embodied in capital equipment that then subsequently allowed the organization of workplaces along more efficient and productive lines. Jorgenson found that technical change was biased and tended to be energy-using i.e. holding all prices constant , the share of costs devoted to energy use tended to increase over time (but see more recent results of Judson et al.). If this is the case, lower energy prices tend to accelerate TFP growth and vice versa.

A fourth possible cause of decoupling is growing autonomous energy efficiency. This is of great interest because limits to this change in technology could be far off. However, Jorgensen and Wilcoxen (1993) estimated that autonomous energy efficiency is declining. Berndt et al (1993) use a model in which this index is assumed to change at a constant rate. They estimate that in US manufacturing industry between 1965 and 1987 the energy augmentation index was increasing at between 1.75% and 13.09% per annum depending on the assumptions made.[4] Judson *et al*. (1999) estimate separate EKC relations for energy consumption in each of a number of energy-consuming sectors for a large panel of data using spline regression. The sectors are: industry and construction, transportation, households and others, energy sector, non-energy uses, and total apparent consumption, as well as households and agriculture which are subsets of households and others. They estimate time effects that show rising energy consumption over time in the household and other sector but flat to declining time effects in industry and construction. Technical innovations tend to introduce more energy using appliances to households and energy saving techniques to industry (Stern, 2002).

Figure 5 presents the autonomous energy efficiency index as estimated by Stern (in press) using the Kalman Filter, an advanced time series technique that can extract unobserved stochastic series from time series data given a theoretical model that defines the trend of interest. This is a more sophisticated approach than the studies cited above that assume that the index follows a simple linear or quadratic time path. Relative to an overall upward trend, the index shows large fluctuations. Until the mid-1960s autonomous energy efficiency is increasing and then it starts a sharp decline. However, the results show that the first oil shock in 1973 does not disrupt the overall downward trend in energy efficiency. Only after the second oil shock does the trend reverse and energy efficiency increase.

The Khazzoom-Brookes Postulate (Brookes, 1990; Khazzoon, 1980) argues that energy saving innovations can end up causing even more energy to be used as the money saved is spent on other goods and services which themselves require energy in their production. Energy services are demanded by the producer or consumer and are produced using energy itself. An innovation which reduces the amount of energy required to produce a unit of energy services lowers the effective price of energy services. This results in an increase in demand for energy services and therefore for energy (Binswanger, 2001). The lower price of energy also results in an income effect (Lovins, 1988) that increases demand for all goods in the economy and therefore for the energy required to produce them. There may also be adjustments in capital stocks that result in an even further increased long-run demand response for energy (Howarth, 1997). This adjustment in cpaital stocks is termed a "macro-economic feedback". Howarth (1997) argues persuasively that the rebound effect is less than

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[4] In Canada the rate of increase was lower while in France a decline was found in their more general models.

the initial innovation induced reduction in energy use, so improvements in energy efficiency do, in fact, reduce total energy demand.

c. Energy Quality and Shifts in Composition of Energy Input

Energy quality is the relative economic usefulness per heat equivalent unit of different fuels and electricity. One way of measuring this is the marginal product of the fuel which is the marginal increase in the quantity of a good or service produced by the use of one additional heat unit of fuel. These services also include services received directly from energy by consumers. Some fuels can be used for a larger number of activitiies and/or for more valuable activities. For example coal cannot be used directly to power a computer while electricity can. The marginal product of a fuel is determined in part by a complex set of attributes unique to each fuel physical scarcity, capacity to do useful work, energy density, cleanliness, amenability to storage, safety, flexibility of use, cost of conversion, and so on. But also the marginal product is not uniquely fixed by these attributes. Rather the energy vectors marginal product varies according to what activities it is used in, how much and what form of capital, labor, and materials it is used in conjunction with, and how much energy is used in each application. Therefore, energy qualities are not fixed over time. However, it is generally believed that electricity is the highest quality type of energy followed by natural gas, oil, coal, and wood and biofuels in descending order of quality. This is supported by the typical prices of these fuels per unit of energy. According to economic theory the price paid for a fuel should be proportional to its marginal product.

Schurr and Netschert (1960) were among the first to recognize the economic importance of energy quality. Noting that the composition of energy use has changed significantly over time (Figure 6), Schurr and Netschert argued that the general shift to higher quality fuels reduces the amount of energy required to produce a dollar’s worth of GDP.

Researchers such as Cleveland et al. (1984), Kaufmann (1992) and OTA (US Congress, 1990) present analyses that explain much of the decline in US energy intensity in terms of structural shifts in the economy and shifts from lower quality fuels to higher quality fuels. Figure 7 illustrates the increase in the second half of the 20th Century in U.S. GDP and a quality adjusted index of energy use computed by Stern (1993). The index accounts for differences in the productivity of different fuels by weighting them by their prices. There is clearly less evidence of decoupling in these data. If decoupling is mainly due to the shift to higher quality fuels then there appear to be limits to that substitution. In particular, exhaustion of low-cost oil supplies could mean that economies have to revert to lower quality fuels such as coal (Kaufmann, 1992).

Berndt (1990) also notes the key role played by the shifting composition of energy use towards higher quality energy inputs. If this is ignored, apparent TFP growth is greater than is really the case - the basic argument was put forward originally by Jorgenson and Griliches regarding capital and energy quality.

Kaufmann (in press) estimates a vector autoregressive model of the energy/GDP ratio, hoursehold energy expenditures, energy mix variables, and energy price variables for the US. he finds that shifting away from coal use and in particular shifting towards the use of oil reduces energy intensity. This shift away from coal made contributes to declining energy intensity over the entire 1929-99 time period.

d. Shifts in the Composition of Output

Typically, over the course of economic development the output mix changes. In the earlier phases of development there is a shift away from agriculture towards heavy industry, while in the later stages of development there is a shift from the more resource intensive extractive and heavy industrial sectors towards services and lighter manufacturing. Different industries have different energy intensities. It is often argued that this will result in an increase in energy used per unit of output in the early stages of economic development and a reduction in energy used per unit output in the later stages of economic development. Pollution and environmental disruption would be expected to follow a similar path (Panayotou, 1993). This argument can be pursued further to argue that the shift to service industries results in a decoupling of economic growth and energy use.

Of course service industries still need large energy and resource inputs. The product being sold may be immaterial but the office towers, shopping malls, warehouses, rental apartment complexes etc. where the activity is conducted are very material - energy is used in their functioning as well as in their construction and maintenance. Other service industries such as transport are clearly heavily resource and energy using. Furthermore, consumers use large amounts of energy and resources in commuting to work, shop etc. Therefore a complete decoupling of energy and growth as a result of shifting to the service sector seems unlikely.

Furthermore on a global scale there may be limits to the extent to which developing countries can replicate the structural shift that has occurred in the developed economies (Stern et al 1996) and, additionally, it is not clear that the developed world can continue to shift in that direction indefinitely.

Cleveland *et al*. (1984) argue that when indirect energy use embodied in manufactured products and services is taken into account the US service and household sectors are not much less energy intensive than the other sectors of the economy and that there is little evidence that the shift in output mix that has occurred in the last few decades has significantly lowered the energy/GDP ratio. Rather changes in the mix of energy used are primarily responsible. However, Cleveland *et al*. (2000) show a negative effect on the energy/GDP ratio of a shift to the service sector in Germany. Kaufmann (in press) finds that reduced energy purchases by households contributed to reducing the energy intensity of GDP in the US after 1999.

Moving to an international context, Stern (2002) found that in a group of 64 countries in the period from 1973 to 1990 the effect of shifting 1% of GDP to the service sector, holding the fuel mix constant and scale of the economy constant, was in fact a 0.03% increase in sulfur emissions while the same shift towards manufacturing resulted in a 0.01% reduction. Heavy industry had a larger positive cofficient as expected. Stern (2002) suggests that this result stems from the correlation between service sector energy use and consumer sector energy use which is not controlled for in the model. Also as technological change was assumed to occur at the same rate in each sector the effects found by Judson et al. (1989), where the consumer sector sees rising energy intensity over time and manufacturing decreasing energy intensity.

A number of other energy or carbon emissions environmental Kuznets curve studies find negative coefficients for the service sector and a positive coefficient for the manufacturing sector (Stern, 1998). But these studies are probably less econometrically reliable (Stern and Common, 2001).

4. Empirical Testing

This section reviews the empirical evidence on the tightness of coupling between energy use and economic output. Ordinary linear regression or correlation methods cannot be used to establish a casual relation among variables. In particular it is well known that when two or more totally unrelated variables are trending over time they will appear to be correlated simply because of the shared directionality. Even after removing any trends by appropriate means, the correlations among variables could be due to causality between them or due to their relations with other variables not included in the analysis. Two methods for testing for causality among time series variables are Granger causality tests (Granger, 1969) and cointegration analysis (Engle and Granger, 1987).

Granger causality tests whether one variable in a relation can be meaningfully described as a dependent variable and the other variable an independent variable, whether the relation is bi-directional, or whether no meaningful relation exists at all. This is usually done by testing whether lagged values of one of the variables significantly adds to the explanatory power of a model which already includes lagged values of the dependent variable and perhaps also lagged values of other variables.

While Granger causality can be applied to both stationary and integrated time series (time series which follow a random walk), cointegration applies only to linear models of integrated time series. The irregular trend in integrated series is known as a stochastic trend as opposed to a simple linear deterministic time trend. Time series of GDP and energy use usually found to be integrated. Cointegration analysis aims to uncover causal relations among variables by determining if the stochastic trends in a group of variables are shared by the series so that the total number of unique trends is less than the number of variables. It can also be used to test if there are residual stochastic trends, which are not shared by any other variables. This may be an indication that important variables have been omitted from the regression model or that the variable with the residual trend does not have long-run interactions with the other variables.

Either of these conclusions could be true should there be no cointegration. The presence of cointegration can also be interpreted as the presence of a long-run equilibrium relationship between the variables in question. The parameters of an estimated cointegrating relation are called the cointegrating vector. In multivariate models there may be more than one such cointegrating vector.

Both of these methods are usually carried out within the context of vector autoregression models. These models consists of group of regression equations in which each dependent variable is regressed on lagged values of itself and of all the other variables in the system.

Many analysts (e.g. Kraft and Kraft, 1978; Akarca and Long, 1980; Yu and Hwang, 1984; Abosedra and Baghestani, 1991) used Granger (1969) causality tests or the related test developed by Sims (1972) to test whether energy use causes economic growth or whether energy use is determined by the level of output in the context of a bivariate vector autoregression. The results have been generally inconclusive. Where significant results were obtained they indicate that causality runs from output to energy use. Erol and Yu (1987) found some indications of a causal relationship between energy and output in a number of industrialised countries with the most significant relationship being for Japanese data between 1950-1982. However, when the sample was restricted to 1950-1973 the relationship was no longer significant. Yu and Choi (1985) also found a causal relationship running from energy to GDP in the Philippines economy, and causality from GDP to energy in the economy of South Korea. In the latter economy, causality from energy to GDP is significant only at the 10% level. Ammah-Tagoe (1990) found causality from GDP to energy use in the Ghana.

Stern (1993) tested for Granger causality in a multivariate setting using a vector autoregression (VAR) model of GDP, energy use, capital, and labor inputs. He also used a quality-adjusted index of energy input in place of gross energy use. The multivariate methodology is important because changes in energy use are frequently countered by the substitution of other factors of production, resulting in an insignificant overall impact on output. Weighting energy use for changes in the composition of energy input is important because a large part of the growth effects of energy are due to substitution of higher quality energy sources such as electricity for lower quality energy sources such as coal (Jorgensen, 1984; Hall *et al.*, 1986; Kaufmann, 1994). When both these innovations are employed, energy is found to Granger cause GDP. These results are supported by Hamilton (1983) and

Burbridge and Harrison (1984), who found that changes in oil prices Granger-cause changes in GNP and unemployment in VAR models whereas oil prices are exogenous to the system.

Ohanian (1988) and Toda and Phillips (1993) showed that the distribution of the test statistic for block exogeneity in a VAR with non-stationary variables is not the standard chi-square distribution. This means that the significance levels reported in previous studies of the Granger-causality relationship between energy and GDP may be incorrect, as both variables are generally integrated series. If there is no cointegration between the variables then the causality test should be carried out on a VAR in differenced data, while if there is cointegration standard chi-square distributions apply when the cointegrating restrictions are imposed. Thus testing for cointegration is a necessary prerequisite to causality testing.

Yu and Jin (1992) were the first to test whether energy and output cointegrate. They found that no such relationship exists between energy use and either employment or an index of industrial production. However, the lack of a long-run equilibrium relationship between gross energy use and output alone does not necessarily imply that there is no relation between the variables. Few analysts believe that capital, labour, and technical change play no significant role in determining output. If these variables are integrated, then there will be no cointegration between energy and output whether there is a relationship between the latter two variables or not. Also, decreasing energy intensity, due to increased energy efficiency, shifts in the composition of the energy input, and structural change in the economy, mean that energy and output will drift apart. Similar comments apply to the bivariate energy-employment relationship. Further, the insensitivity of the test may be compounded by using of total energy use in the economy as a whole but measuring output as industrial output alone.

Masih and Masih (1996) found cointegration between energy and GDP in India, Pakistan, and Indonesia, but no cointegration in Malaysia, Singapore, or the Philippines. Granger causality runs from energy to GDP in India but in the opposite direction in the other two countries. Again, bivariate methods yield indeterminate results.

It would seem that if a multivariate approach helps in uncovering the Granger causality relations between energy and GDP a multivariate approach should be used to investigate the cointegration relations among the variables. Stern (2000) investigated the time series properties of GDP, quality weighted energy, labor, and capital series, estimating a dynamic cointegration model using the Johansen methodology. The cointegration analysis showed that energy is significant in explaining GDP. It also showed that there is cointegration in a relationship including GDP, capital, labor, and energy. This result contradicts Yu and Jin's (1992) bivariate analysis for the United States and Masih and Masih’s (1996) for all countries apart from India. This study differs from those two by including capital and labor variables and using a quality weighted index of energy input. The multivariate analysis shows that energy Granger causes GDP either unidirectionally or possibly through a mutually causative relationship depending on which version of the model is used.

Glasure (2002) also investigates the role of omitted variables in the energy income relation in Korea though the variables he investigates reflect fiscal and monetary policy – real money and real government expenditure. There is weak evidence of cointegration and bidirectional causality between energy and income in this model.

These results support the results of Stern (1993) regarding Granger causality between energy and GDP. The results strengthen Stern’s previous conclusions that energy is a limiting factor in economic growth. Shocks to the energy supply will tend to reduce output.

5. Environmental Implications

a. Theory

This article has argued that there is a very strong link between energy use and both the level of economic activity and economic growth. What are the implications of this linkage for the quality of the environment? I focus here on immediate environmental impacts. Issues of sustainabiltiy were discussed in section 2 above.

Energy use has a variety of impacts. Energy extraction and processing always involves some forms of environmental disruption including both geomorphological, and ecological disruption as well as pollution. Energy use involves both pollution and other impacts such as noise from transport, and land use impacts such as the construction of roads etc. As all human activities require energy use, in fact all human impacts on the environment could be seen as the consequences of energy use. In this way energy use is sometimes seen as a proxy for environmental impact of human activity in general (Common, 1995). Creation of "order" in one part of the system creates a greater degree of disorder elsewhere – creating order in the economic system always implies creating disorder in nature though this could be in the sun or space. Disruption of nature can never be eliminated entirely.

The factors that reduce the total amount of energy needed to produce a dollar’s worth of GDP, discussed in section 3, therefore, also act to reduce the environmental impact of economic growth in exactly the same way as they reduce energy consumption. However, not all impacts of energy use are equally harmful to the environment and human health.

A shift from lower to higher quality energy sources not only reduces the total energy required to produce a unit of GNP but also may reduce the environmental impact of the remaining energy use. An obvious example would be a shift from coal use to natural gas use. Natural gas is cleaner burning and produces less carbon dioxide per unit of energy derived. However, we need to be careful here. Nuclear generated electricity is a higher quality fuel than coal, at least as measured by current prices, but its long-term environmental impacts are not necessarily lower. Incorporating the cost of currently unpriced environmental externalities into the prices fuels would, though, raise the apparent quality of those fuels. This isn’t a contradiction, as a higher market price would mean that those fuels would only be used in more productive activities (Kaufmann, 1992).

The environmental impact of energy use may also change over time due to technological innovation that reduces the emissions of various pollutants or other environmental impacts associated with each energy source. This is in addition to general energy conserving technological change that reduces the energy requirements of production, already discussed above.

Therefore, despite the strong connections between energy use and economic growth there are several pathways through which the environmental impact of growth can be reduced. Again, however, if there are limits to substitution and technological change then the potential reduction in the environmental intensity of economic production is eventually limited. Innovations that reduce one type of emission, for example flue gas desulfurization, often produce a different type of waste that must be disposed of – in this case gypsum possibly contaminated with heavy metals - as well as other disruptions required to implement the technology – in this example limestone mining.

b. Empirical Evidence: The Environmental Kuznets Curve

In the 1970s the debate on the relation between growth and the environment focused on the report of the Club of Rome: “The Limits to Growth”. The common wisdom was that economic growth meant greater environmental impacts and the main way to environmental gains was reduced population and consumption. Economists and others argued that substitution and innovation could reduce environmental impacts as we described in section 2 above. But these were minority views. The mainstream view was that environment and economy were conflicting goals. By the late 1980s, however, with the emergence of the idea of sustainable development, the conventional wisdom shifted to one of “too poor to be green”. Less developed countries lacked the resources for environmental protection and growth and development was needed to provide for environmental protection. This idea was embodied in the empirical models that became known as "Environmental Kuznets Curves" (EKC).

This hypothesis states that there is an inverted U-shape relation between various indicators of environmental degradation and income per capita with pollution or other forms of degradation rising in the early stages of economic development and falling in the later stages. The EKC is named for the economist Kuznets who hypothesized that the relationship between a measure of inequality in the distribution of income and the level of income takes the form of an inverted U shape curve. However, Kuznets had no part in developing the EKC concept.

This idea has become one of the "stylised facts" of environmental and resource economics (e.g. Stokey, 1998). This is despite considerable criticism on both theoretical and empirical grounds (e.g. Stern *et al*. 1996; Ansuategi *et al*., 1998; Ekins, 1997; Stern, 1998; Stern and Common, 2001). The EKC has been interpreted by many as indicating that no effort should be made to adopt environmental policies in developing countries – when those countries become rich the current environmental problems will be addressed by policy changes adopted at that later time (e.g. Beckerman, 1992). As a corollary it is implied that little in the way of environmental clean-up activity is being conducted in developing countries. These views are challenged by recent evidence that, in fact, pollution problems are being addressed and remedied in developing economies (e.g. Dasgupta et al., 2002). In addition to the data and case studies provided by Dasgupta et al. (2002), Stern (2002) and Stern and Common (2001) show that for sulfur– widely believed to show the inverted U-shape relation between emission and income per capita – emissions in fact rise with increasing income at all levels of income, but that there are strong time effects reducing emissions in all countries across all income levels. In our opinion, this new evidence supersedes the debate about whether some pollutants show an inverted U-shape curve and others – for example carbon dioxide and "new toxics" (Dasgupta et al., 2002) - a monotonic relationship. All pollutants show a monotonic relation with income, but over time pollution has been reduced at all income levels, *ceteris paribus*. Similarly the debate about whether the downward sloping portion of the EKC is an illusion resulting from the movement of polluting industries to offshore locations is also now moot. This phenomenon might lower the income elasticity of pollution in developed economies relative to developing economies, but it does not seem sufficient to make it negative. The true form of the emissions-income relationship is a mix of two of the scenarios proposed by Dasgupta et al. (2002) illustrated in Figure 8. The overall shape is that of their "new toxics" EKC - a monotonic increase of emissions in income. But over time this curve shifts down. This is analogous to their "revised EKC" scenario, which is intended to indicate that over time the conventional EKC curve shifts down.

While the environmental Kuznets curve is clearly not a "stylised fact" and is unlikely to be a useful model, this does not mean that it is not possible to reduce emissions of sulfur and other pollutants. The time effects from an EKC estimated in first differences (Stern and Common, 2001) and from an econometric emissions decomposition model (Stern, 2002) both show that considerable time related reductions in sulfur emissions have been achieved in countries at many different levels of income. Dasgupta et al. (2002) provide data and case studies that illustrate the progress already made in developing countries to reduce pollution. In addition, the income elasticity of emissions is likely to be less than one - but not negative in wealthy countries as suggested by the EKC hypothesis. In slower growing economies, emissions-reducing technological change can overcome the scale effect of rising income per capita on emissions. As a result, substantial reductions in sulfur emissions per capita have been observed in many OECD countries in the last few decades. In faster growing middle income economies the effects of rising income overwhelm the contribution of technological in reducing emissions.

This picture relates very closely to the theoretical model described in the previous subsection (5a). Overall there is a strong link between rising energy use, economic growth, and pollution. However, the linkages between these three can be mitigated by a number of factors including shifting to higher quality fuels and technological change aimed at both general increases in economic productivity and specifically at reducing pollution. However, given the skepticism regarding the potential for unlimited substitution or technological progress expressed earlier in this article, there may be limits to the extent that these linkages can continue to be loosened in the future.

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Figure 1. The Neoclassical Growth Model

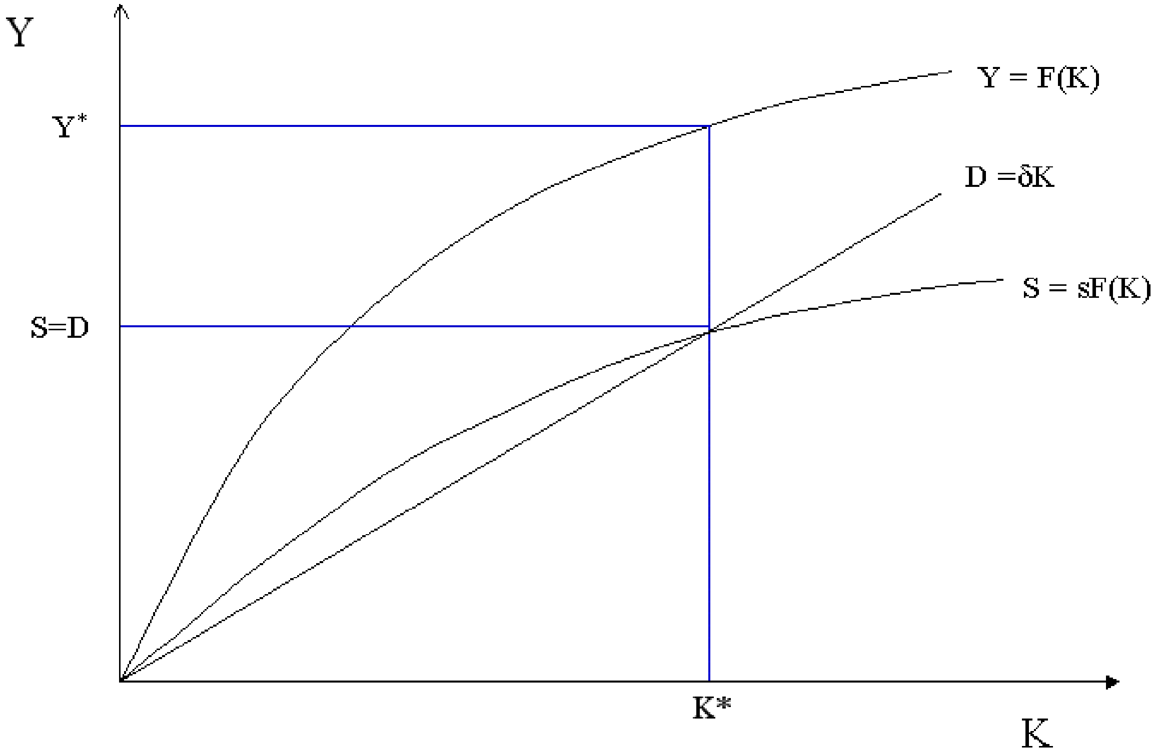


Figure 2. The Elasticity of Substitution

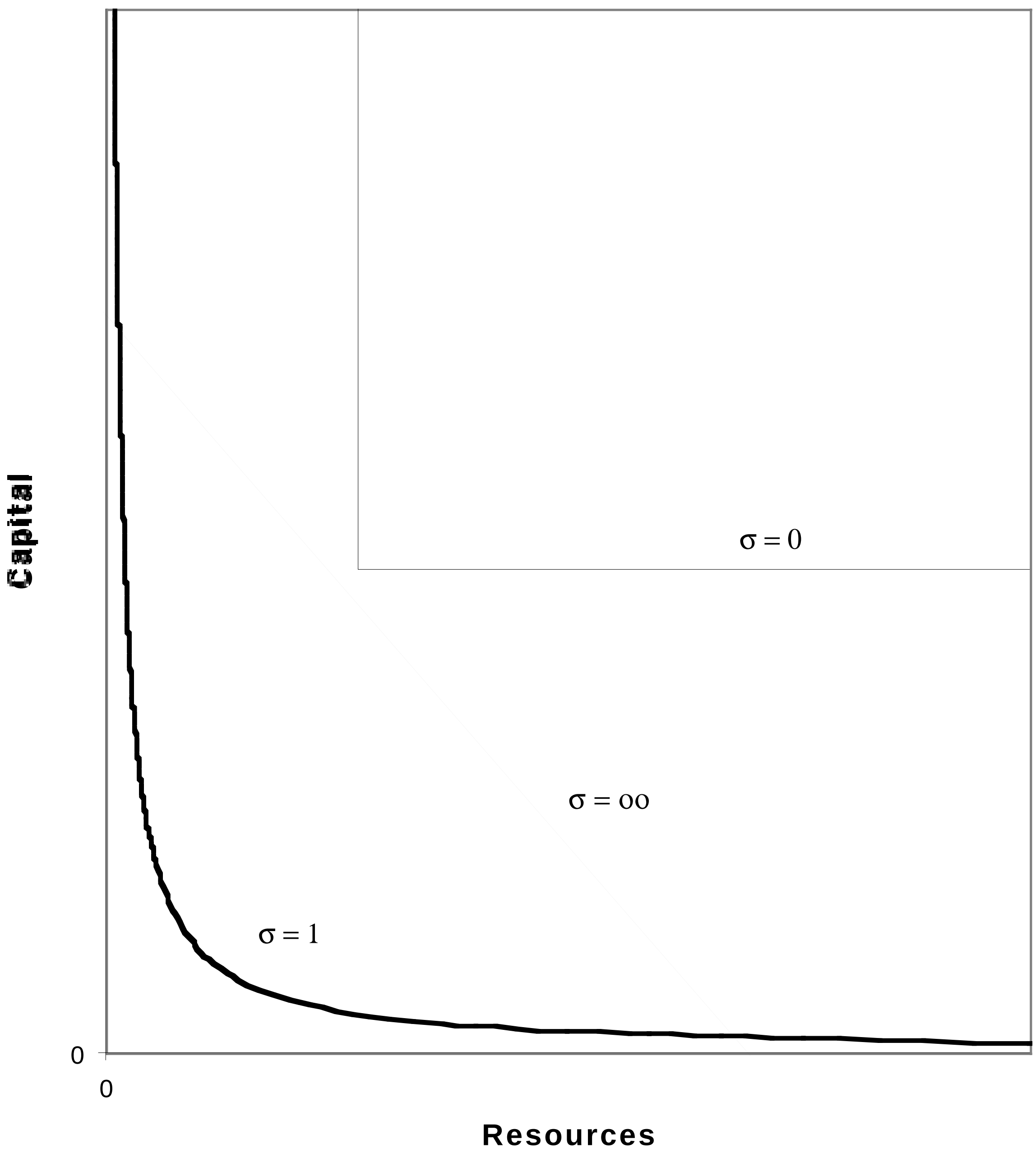


Figure 3. Macro-Level Limits to Substitution

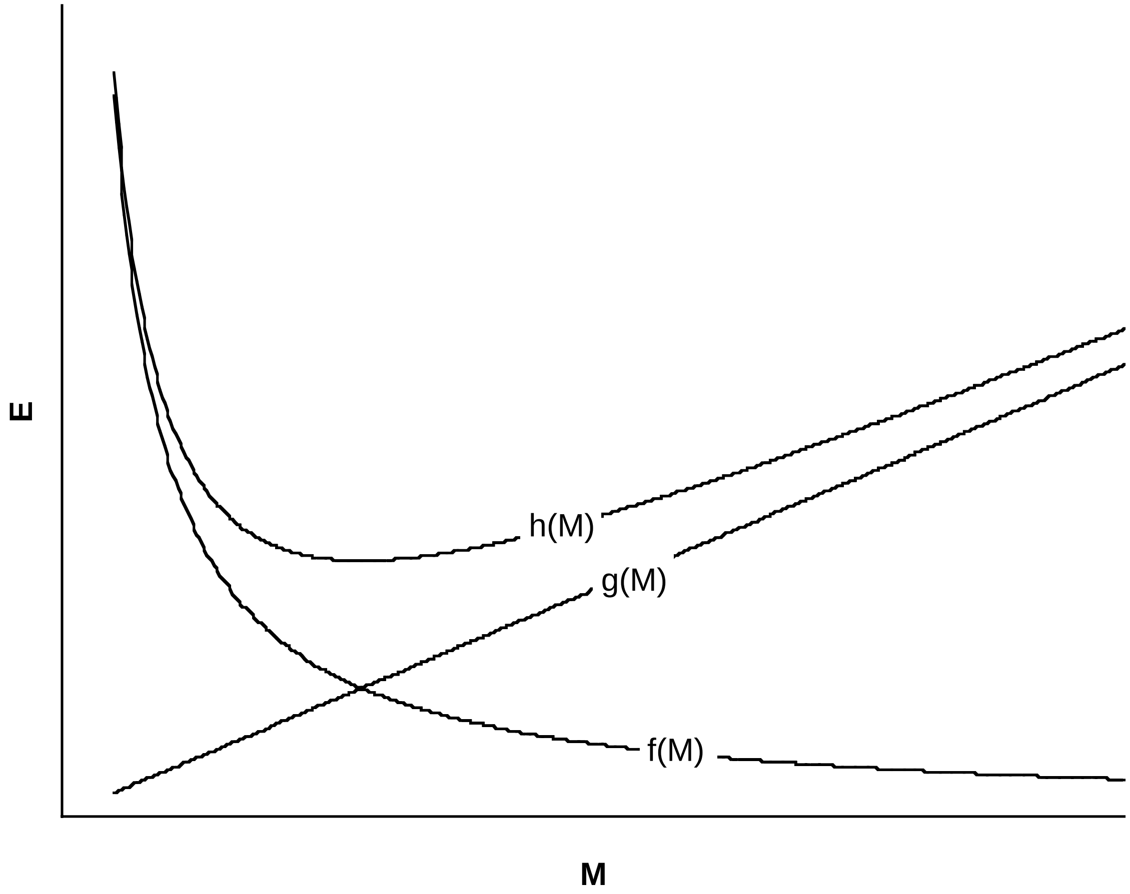
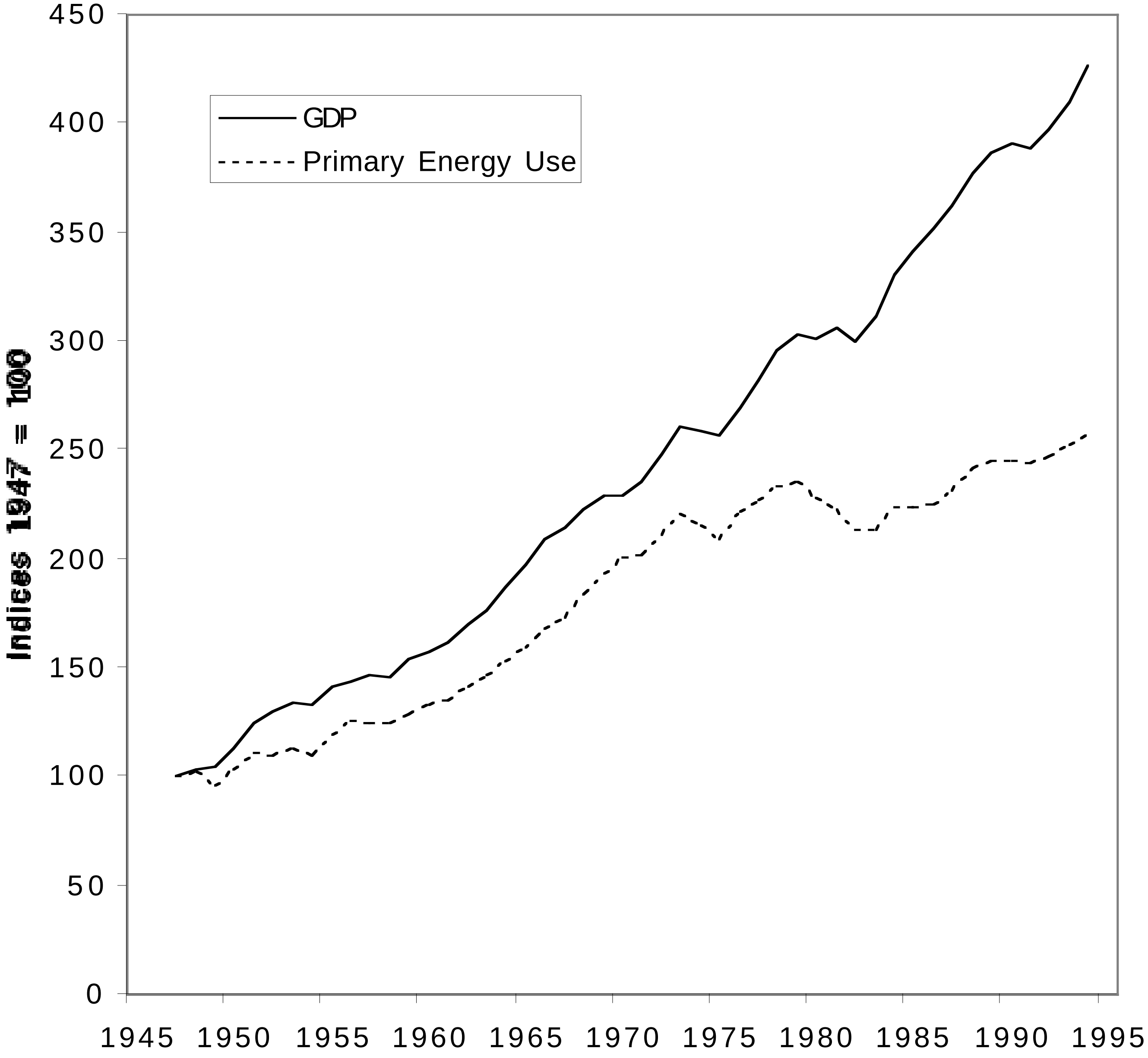


Figure 4. U.S. GDP and Primary Unadjusted Energy Use



Notes: GDP is in constant dollars i.e. adjusted for inflation. Energy use is the sum of primary energy BTUs.

Figure 5. U.S. Autonomous Energy Efficiency Index

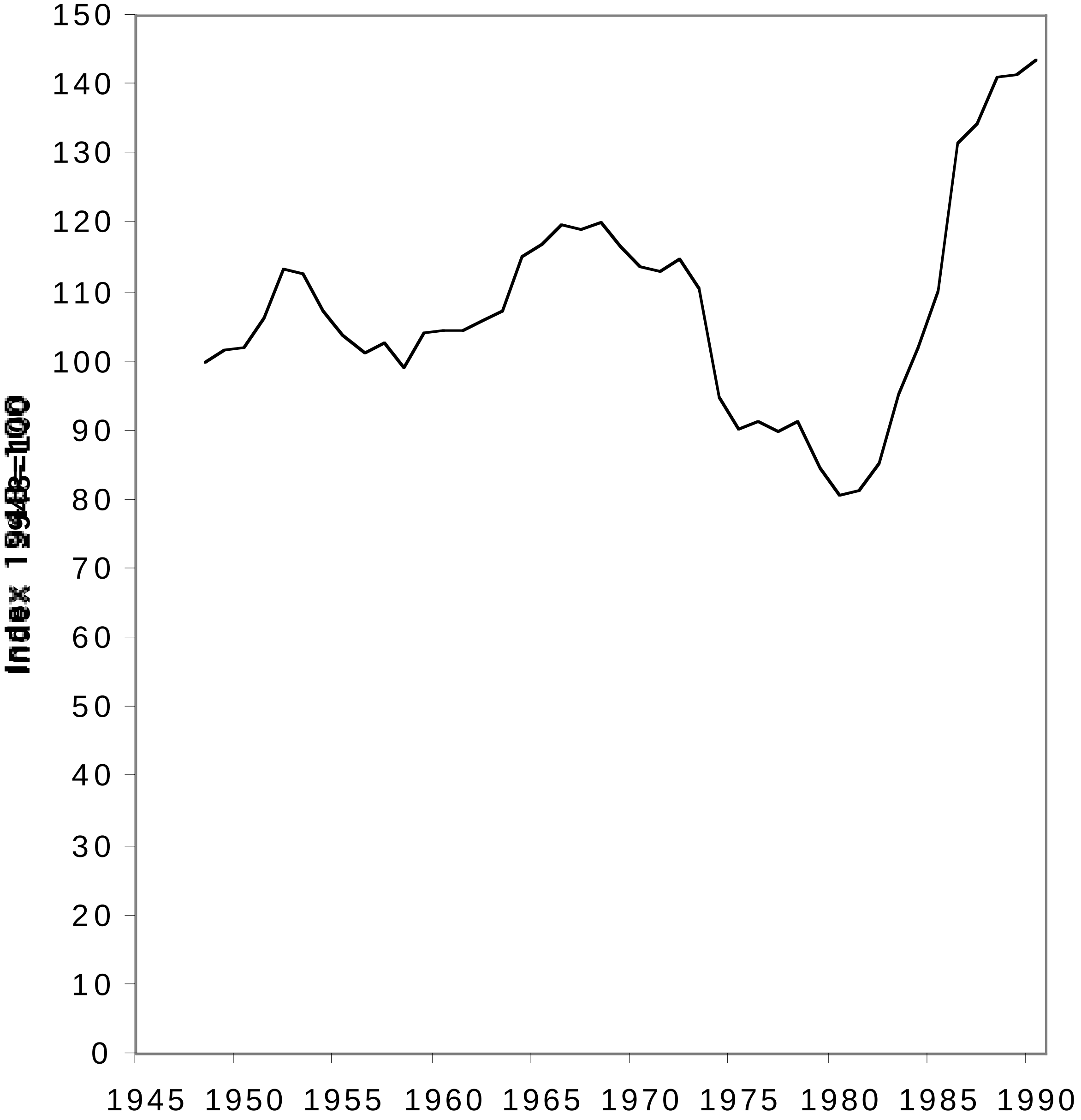


Figure 6. Composition of US Energy Input

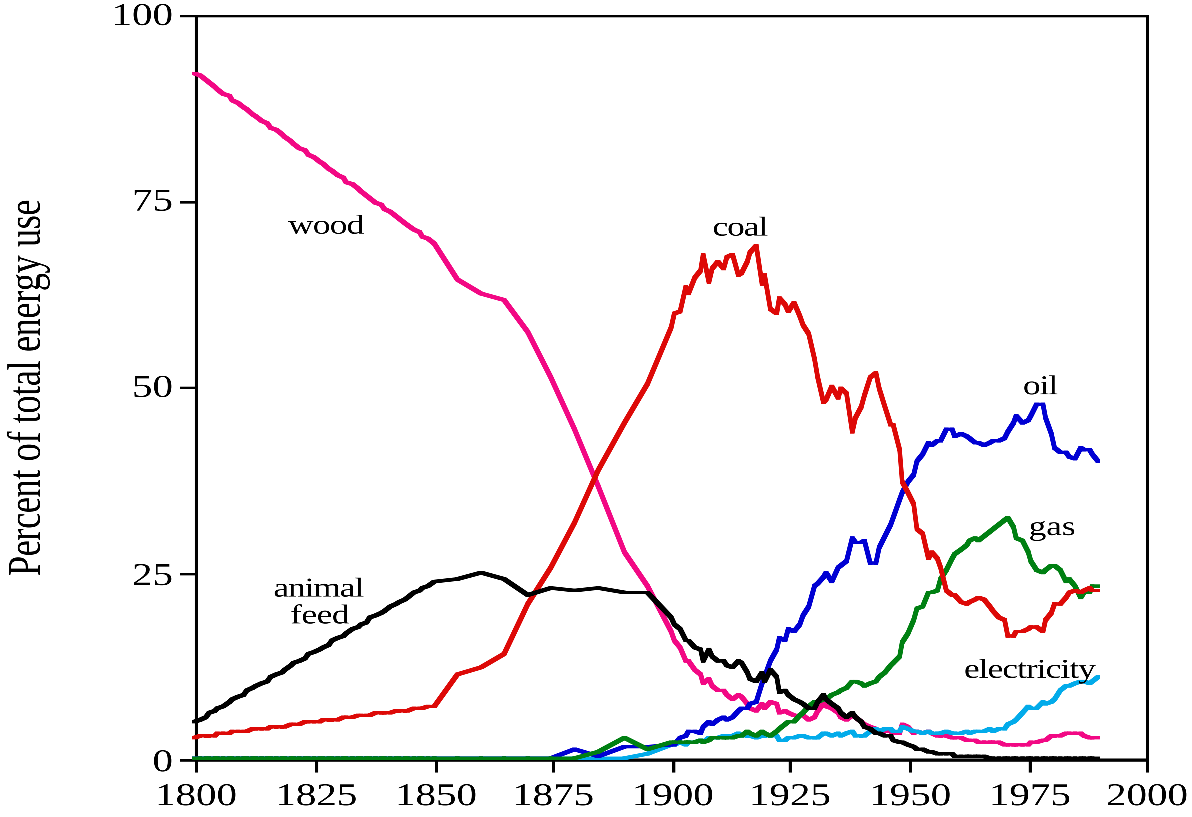
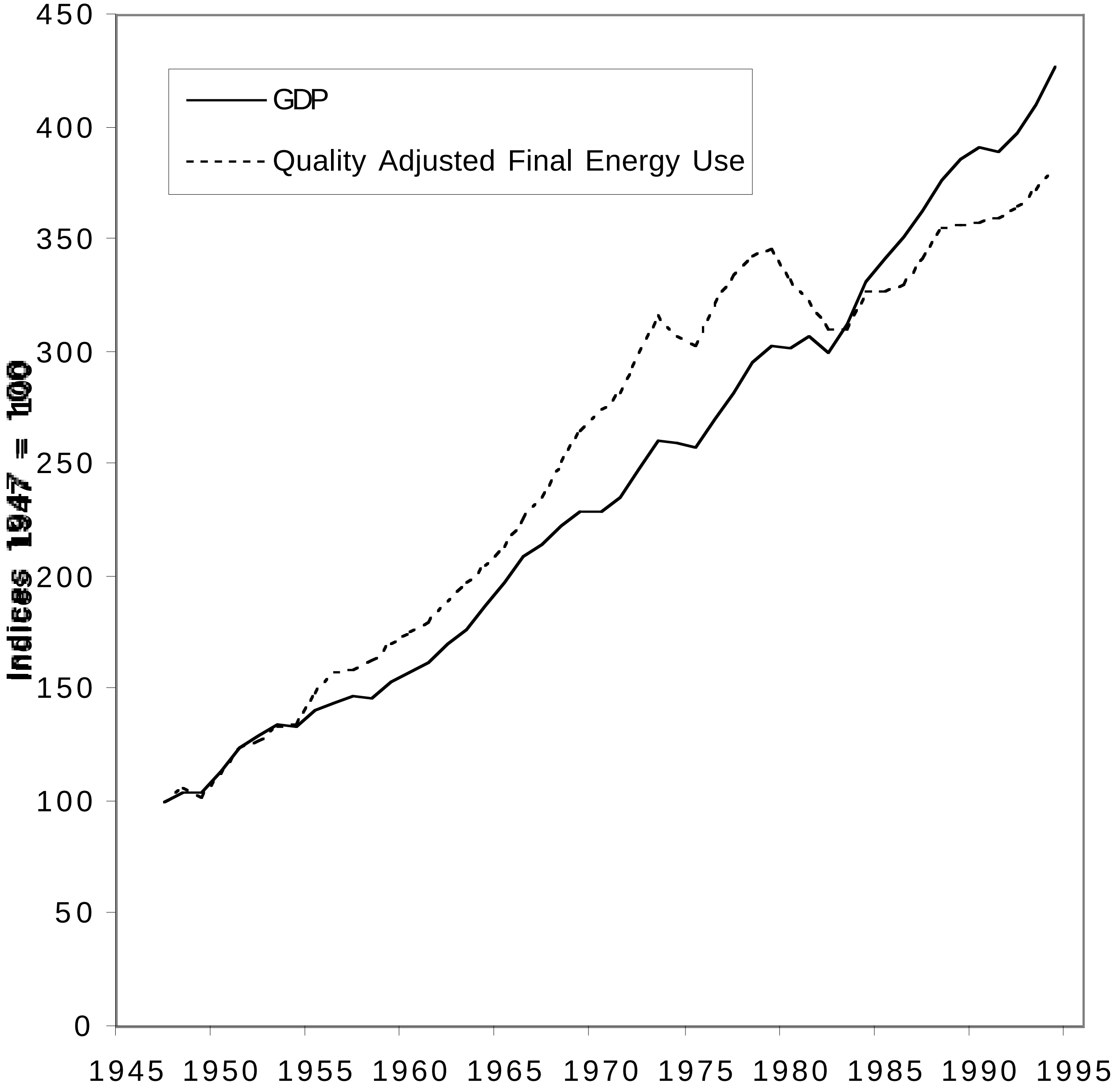
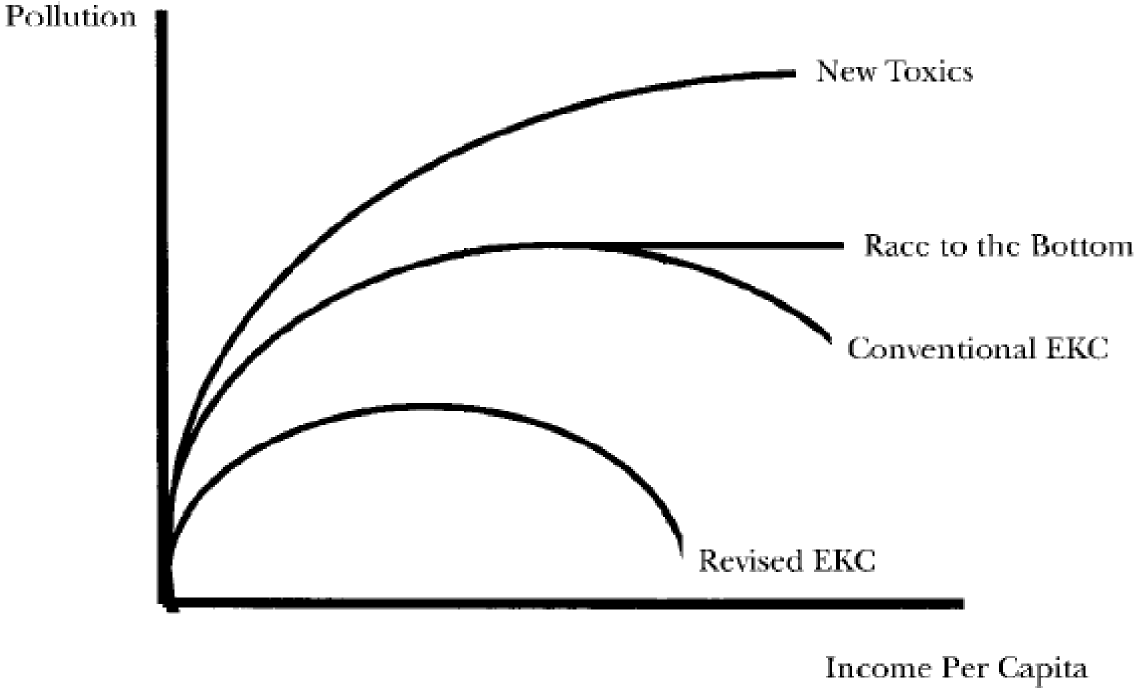


Figure 7. U.S. GDP and Quality Adjusted Final Energy Use



Notes: GDP is in constant dollars i.e. adjusted for inflation. Energy use is a Divisia index of the principal final energy use categories – oil, natural gas, coal, electricity, biofuels etc. The different fuels are weighted according to their average prices.

Figure 8. Environmental Kuznets Curve: Different Scenarios



Source: Dasgupta *et al*. (2002)