TOWARDS AN ENDOGENOUS THEORY OF ECONOMIC GROWTH

by

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Towards an Endogenous Theory of Economic Growth

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Abstract

This paper proposes a new approach to growth theory. The rationale is two-fold. First of all, the old (Solow-type) theory is increasingly unable to explain the "stylized facts" of growth. These are well known and it is unnecessary to summarize the difficulties. The second part of the rationale is that the standard theory is based on so-called neoclassical "microfoundations" that are both internally inconsistent and unnecessary.

The new approach has three important features. First, it acknowledges the importance of natural resources as a driver of past and present economic growth, especially in the context of substituting mechanical power for human labor. Second, it introduces a new composite form of production function explicitly reflecting the fact that the important (i.e. scarce) factors of production in economics can and do change over time, from a "cowboy" economy of the past to a "spaceship" economy of the future. Whereas in the cowboy era non-renewable natural resources were readily available and could properly regarded as intermediate products of scarce labor and produced capital, this is increasingly untrue. In the future spaceship era non-renewables, including environmental resources, will be scarce and limiting whereas human labor and produced capital will no longer be scarce.

The third new feature is that, in place of technical progress term that is a calculated residual, the new model proposes an explicit quantitative measure of the state of technology, *A(t)*. This measure is based on the efficiency of converting natural resources (exergy) into final services. It is estimated (approximately) for the U.S. since 1800 (Appendix A). To fully endogenize the model, it will be necessary to incorporate an explicit link between current economic activity and the state of technology as defined above. This is a task for future research.

Background: Neoclassical Production Theory

Until the late 19th century there was no real theory of production because of a lack of clarity with regard to production itself: what was a gift of nature and what was produced by man. Animals reproduce themselves, but they must be bred, fed, guarded and (in the case of dogs and horses) trained. Land is unproductive until it has been cleared, plowed, and otherwise improved by labor. Labor, in turn, is unproductive without land, animals or other raw materials to work on, not to mention training, supervision, organization and motivation.[1] With regard to agriculture these ambiguities were never fully resolved, but they gradually became less important as manufacturing and trade became more so. Gradually land, animals, structures, roads and machines all came to be seen as productive in some similar — if undefined — sense, although not without the application of human labor. Thus the concept of aggregate capital was born.[2]

Agriculture and agricultural capital (land) has continued to be treated as a special case, however, when it is not ignored altogether. This is because land (as capital) is clearly subject to declining returns to inputs of labor and other forms of capital, whereas manufacturing is characterized by increasing returns. I return to this point later.

Nevertheless, while acknowledging that non-agricultural capital is an intermediate that is produced from labor (and pre-existing capital), most 19th and 20th century economists have, until recently, assumed that abstract labor services (L) and abstract capital services (K) are the two independent but complementary factors of production, either of which can be substituted (in effect) for the other, although not necessarily without limits. Other generally invoked criteria for factors of production appear to be as follows: *scarcity*, *essentiality* and *exogeneity*.

Neoclassical production theory began in the late 19th century with the so-called "marginalist revolution", which related values (prices) to incremental units of scarce commodities. Scarcity need not be more precisely defined, perhaps. It may be enough to say that from an economic perspective a scarce factor is generally one with a non-zero marginal price, although admittedly this is a circular definition. An essential resource (or factor) is one without which there can be no production at all. Some unpriced resources (such as clean air or fresh water) are clearly scarce, even essential. Exogeneity means that the factor pre-exists or is produced outside the economic system. This last condition does not apply to capital, of course, except in the very short run (which may be why Marxists did not consider capital to be a factor).

The neoclassical theory also assumed a declining marginal utility of consumption, and (by analogy) declining marginal productivities for each scarce factor of production. This has been characterized as the "discovery of calculus as applied to economics" [Christensen & Fritz 1981]. But, marginal productivity theory, applied to material products, violates the laws of physics "by implicitly permitting [applications of] labor or capital to create, or destroy, material and energy inputs" [Ayres 1978 p. 40]. Stated more elegantly, "the ability to obtain positive increments of output from the successive application of one input to other factors is a version of *creatio ex nihilo* for it systematically neglects the matter and energy flows required in production" [Christensen & Fritz *op cit*].

In other words, the neoclassical assumption that there are positive (if declining) returns — incremental increases to output — from adding an increment of abstract labor input to a fixed stock of abstract capital, or *vice versa*, only works if the output is also intangible i.e. non-physical. If the output is material, marginal productivity theory amounts to producing something tangible and material from something intangible and immaterial. This is a contradiction of the physical law of conservation of mass/energy.[3] In short, the neoclassical theory of production as originally formulated is not applicable, *in principle*, to material products.

The relevance of resource flows to production and growth is one of three major topics addressed in this paper. The second major topic is technological change and it's measurement. The paper proposes a new proxy for the state of technology, namely the technical efficiency with which exogenous resource flows (exergy inputs) are converted into final services. (Exergy is, roughly, the fraction of energy that is available to do useful work; it is defined later). Technical efficiency increases irreversibly as knowledge accumulates. It is, consequently, a monotonically increasing function of time. Methods of quantifying this measure, at the sectoral level, are discussed.

Finally, the paper proposes a new `meta' production function that implicitly reflects shifting scarcities over long time periods. However, the proposed production function is an explicit function of technical efficiency, not time *per se*. Since technical efficiency — as defined above — can be defined and (approximately) quantified at the sectoral level we have, in principle, a new approach to forecasting long term economic growth.

The E/GNP Ratio and the Kuznets `Inverted U' Curve

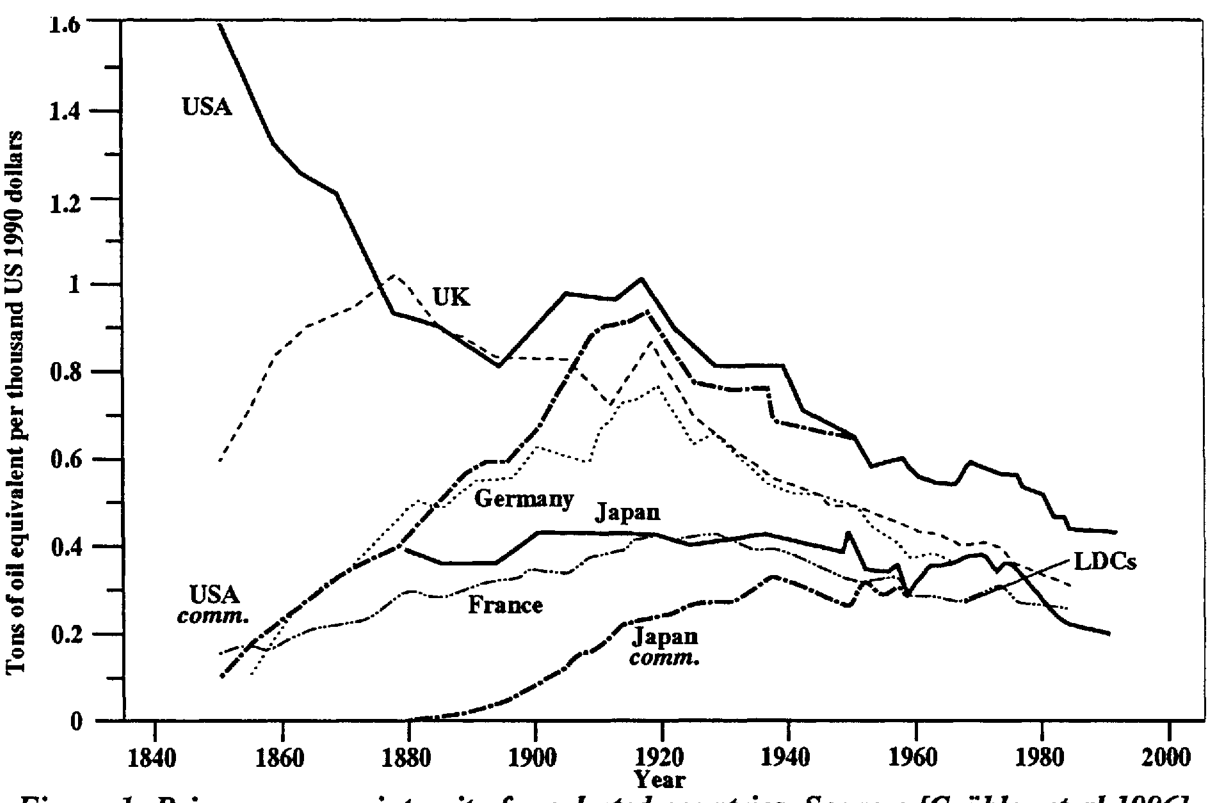
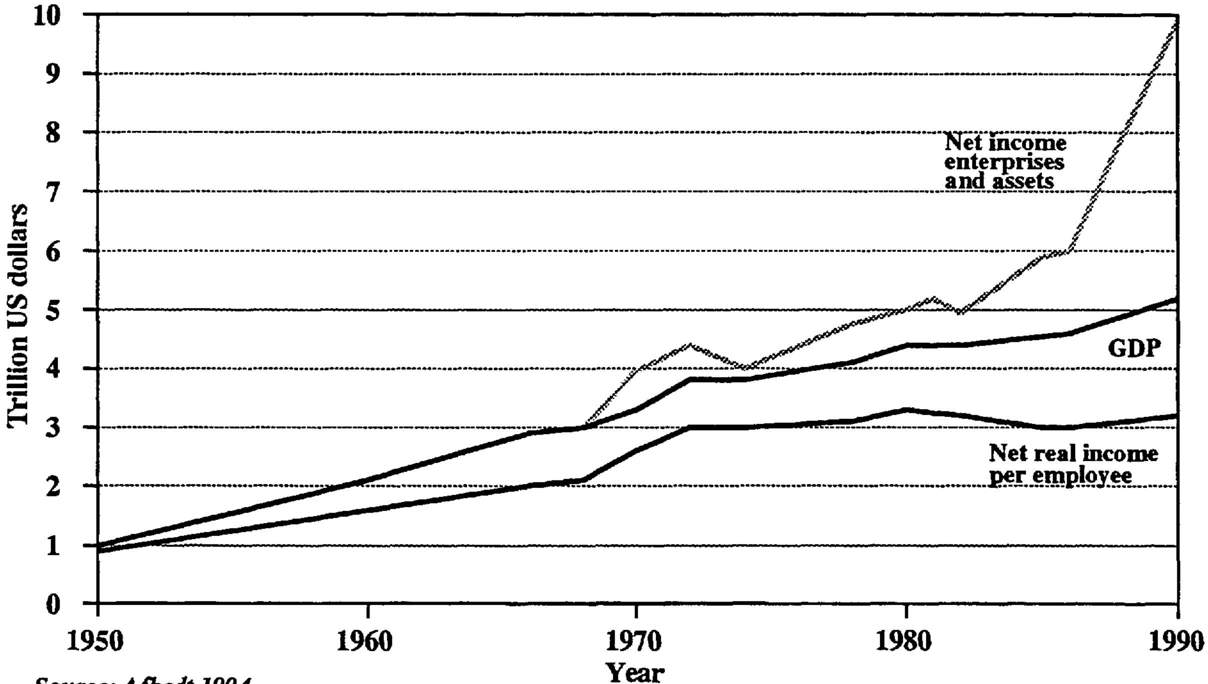


Figure 1: Primary energy intensity for selected countries. Source: [Grübler et al 1996]

One of the stylized facts of long term economic growth and development, that has attracted renewed attention recently, is the so-called Kuznets (inverted U) curve.[4] This pattern suggests that during the early stages of industrialization GNP tends to be increasingly dependent on commercial energy, whereas after some point in the developmental pattern commercial (ant total) energy requirements per unit output begin to decline as services begin to dominate material production. This is an empirical observation that has been qualitatively repeated for a number of countries. The importance of non-commercial energy during the early stages of industrialization, especially for domestic heating and cooking, is clear from *Figure 1* [Grübler *et al* 1996]. In most countries this domestic fuel consists of agricultural wastes or wood harvested from public lands. It largely accounts for the deforestation that is now occurring in Asia and Africa and which took place in colonial America, largely to clear land for planting crops.



Source: Afhedt 1994

Note: Until around 1980 income from both labor and capital grew more or less in parallel with GDP Growth. Since 1980 labor's share fell while the capital share grew sharply.

Figure 2: Changing shares of capital & labor in US agriculture Source: Steinhart & Steinhart 1974]

The natural interpretation of the E/GNP curve is that energy inputs are complementary to capital and labor at the early stages of industrial buildup because infrastructure creation requires earth moving machines that are powered by commercial energy as well as energy intensive materials such as steel, aluminum and cement. On the other hand, later in the process, the relationships change and capital increasingly substitutes for energy. For instance, the substitution of wood stoves for open fireplaces for domestic heating in the U.S. resulted in a fourfold reduction in fuel consumption per unit of heat output [Schurr & Netschert 1960, p. 49, footnote]. The substitution of electric drive for steam power in factories early in this century also increased energy efficiency [Devine 1982]. Increasing compression ratios of automobile engines from 1920 to 1950 (which became possible thanks to higher octane fuels) resulted in dramatic increases in fuel economy [Ayres & Ezekoye 1991]. Diesel engines are more expensive but use less fuel than gasoline engines. More and better insulation reduces the need for space heating. Similarly heat exchangers and recuperators increase efficiency but cost money. During the later stages of industrialization machines driven by commercial energy also substitute increasingly for human labor. Modern agriculture is a particularly good example of this substitution (*Figure 2*) [Steinhart & Steinhart 1974].

In short, the *complementary* relationship between capital, labor and energy use dominates in the early stages of industrialization. The *substitution* relationship becomes increasingly important over time, however. As capital becomes less scarce the substitution relationship becomes dominant. This complex dynamic behavior is obviously incompatible with a constant elasticity of substitution that is characteristic of a traditional production function of the Cobb-Douglas or CES type, in which E is included as a multiplicative factor.[5] In reality, the elasticity of substitution between capital and energy is clearly some function of the level of development and the level of technology.

Exergy and Technological Progress

Anticipating later discussion, it is helpful to have a general measure of heterogeneous resource flows. Most analysts have considered energy (E) and materials (M) flows separately. But the term "energy" is not used correctly in most economic studies (including the otherwise authoritative work by Schurr & Netschert cited in the previous section), leading to unnecessary confusion with regard to the treatment of heterogeneous sources, such as hydroelectricity, fossil fuels, nuclear power, solar power, wind and firewood.

Similarly, total mass is a very unsatisfactory measure for heterogeneous material inputs (or outputs). For these reasons, economists have been forced to use monetary measures (dollar value) exclusively, despite many problems. It is quite acceptable to compare monetary outputs per unit of aggregate mass input, over time, or between countries, for a given industry (say steel, or petrochemicals). But comparing one sector with another in this manner introduces serious conceptual difficulties. While mass is definable for all materials, and hence mass inputs and outputs are definable for all sectors, the relationship between aggregate mass input and monetary outputs cannot meaningfully be compared, either between sectors or from period to period. A better measure of resource inputs is needed.

Technically, as I have said, the word *energy*, as used in business, government and economics, is inaccurate. What is normally measured in practice on the input side is heat or potential heat of combustion (technically, *enthalpy*), while on the output side the usual measure is *mechanical work* or power delivered over time. Electric power is a pure form of work. (That is, it can be converted into work with almost 100% efficiency). Energy is a conserved quantity. It is neither gained nor lost in the economic process and hence cannot be a factor of production. For the sake of conceptual precision it should be replaced by the word *exergy*, which refers to that part of the energy flux that is available to do useful work and, which can be used up in an economic process as work is done and energy becomes less available.[6]

All of this confusion can be avoided by using exergy as an alternative measure of potential work. As applied to fossil fuels it is nearly equal to the standard heat of combustion. In the case of hydroelectricity, or wind power, it is nearly equal to the electric power output. In the case of steam, at temperature T, it is equal to heat content times the Carnot factor $(T-T_0)/T$ where T_0 is the ambient temperature of the surface of the earth.[7] In the case of nuclear and solar power special calculations are needed, depending on the details of the assumed conversion process.

As it happens, the exergy content of (dry) fossil hydrocarbons is very nearly equal to their heat of combustion, thanks to the fact that combustion generates rather high temperatures (over 1500°C). This heat can be converted to work, *in principle*, with comparably high Carnot efficiency. The same cannot be said of firewood, which burns at much lower temperatures (even when comparatively dry) and wastes much of it's heat output on vaporizing water. But the fact that fossil fuels are so dominant, at present, has encouraged energy analysts to measure energy in terms of heat (e.g. BTU) and to speak of coal or oil equivalents. But hydroelectricity can only be related to heat by an awkward convention, and nuclear heat is only meaningful in the context of a specific nuclear power system.

Exergy is definable for all materials, not just fuels. The exergy measure applies equally well to organic materials and inorganic substances. Thus it can be determined equally well for physical process inputs (resource flows, including fuels), process outputs (material products and byproducts), waste heat, and material waste effluents. It is as fundamental a measure as mass, except that it is only defined jointly for a material and the environmental medium or reference state with which it must ultimately reach thermodynamic equilibrium. Once the reference state has been specified (usually the atmosphere, ocean or earth's crust) exergy can be calculated quite precisely from thermodynamic data that are already collected and compiled in reference books [see Ayres *et al* 1997-a].

Since the exergy measure is applicable to and computable for *all* materials, as well as all forms of energy, it can be used for purposes of aggregation in situations where the monetary measure is inappropriate or inadequate. For instance, the *stock* of all known mineral resources in a given country, at a given time, can be presented as a single number combining fossil fuels, metals and other minerals. Similarly, the consumption of all resource inputs to a country or an industry — including minerals, agricultural and forest products — can be expressed as an aggregate in exergy terms. This approach to resource accounting has been proposed, in particular, by Wall [Wall 1977, 1986, 1990]. By the same token, the aggregate output of useful products, as well as the generation of material wastes, can also be expressed, separately, in exergy terms [Ayres *et al* 1997-a]. Hereafter the generalized resource flows are assumed to be defined in exergy units.[8]

Simple Production Functions and Simple Models

The Cobb-Douglas production function [Cobb & Douglas 1928; Douglas 1948], and the so-called CES function that was introduced later [Arrow *et al* 1961] are still much used. When only two factors of production (abstract labor and abstract capital) are introduced, these homogeneous functions are not only mathematically simple and convenient, but with one further condition (that they be of order unity) they automatically satisfy the Euler theorem. This is a property that is intuitively very attractive: it implies constant returns to scale at the aggregate level. This feature is essential to the Marshallian thesis of selfreinforcing competitive equilibrium.[9]

Moreover, the exponents of labor and capital in the multiplicative Cobb-Douglas function also has a natural and seductive economic interpretation as marginal rates of return to labor and capital respectively. Invoking the standard neoclassical assumption that labor and capital markets are in equilibrium these, in turn, can be equated to labor and capital "shares" of economic output. In other words, the marginal return to labor is interpreted as fractional payments to labor (wages and salaries as a fraction of GNP) while marginal returns to capital are interpreted as payments to capital (interest, dividends and rents as a fraction of GNP).[10] By definition, GNP is the sum of these two categories of payments. So, if we further assume that GNP is equal to total output, we have, by a circular feat of logic, "confirmed" that economic growth in equilibrium is fully explainable by these two factors of production, and no others.

Solow provided the link between neoclassical theory and empirical growth accounting work that started in the 1950s. It was his work that provided the apparent justification for assuming a constant exogenous rate of technological change and incorporating it into the production function as a simple multiplier of the form e^{-rt}. Using data covering the years 1909–1949 Solow estimated that the rate of technological progress was 1.5% per annum. It should be noted that Solow did not initially assume the Cobb-Douglas form, nor did he assume neutral technological progress or constant shares in his estimating equation. However, shares were in fact relatively constant during the period he analyzed, and he found no correlation between output and changes in the capital labor ratio. This enabled him to conclude that the aggregate production function was in fact neutral and approximately C-D in form.[11]

Of course, the C-D and CES functions also imply unlimited substitutability between the two intangible factors. Implicitly, abstract capital alone, or abstract labor alone, would suffice to produce all economic output. The impossibility of producing a real *material* product from intangible inputs has already been noted. Yet the C-D function, because of it's deceptive mathematical simplicity, has been utilized by a number of theorists for purposes of addressing questions in the domain of resource economics, even where this problem cannot be legitimately glossed over.

In particular, the question whether resource scarcity would constrain long run economic growth was taken up from a theoretical perspective in the 1970s. This was largely in response to the worldwide publicity associated with the publication of the famous Report to the Club of Rome [Meadows *et al* 1972] It is not necessary to recapitulate the discussion in detail. Suffice it to say that a number of leading theoreticians explored variations of economic growth models in which "resources" (meaning exergy) were given some explicit role. The general conclusion was that resource scarcity would not limit economic growth in the long run, given continued capital investment and technological progress.

In most of these models, however, something like a Cobb-Douglas production function was assumed, together with its implication that labor, human capital and natural capital (i.e. resources) are inherently substitutable *without limit* [e.g. *RevEcon* 1974; Solow 1974; Stiglitz 1974, 1979]. Only a few mainstream theoreticians at that time even acknowledged that natural resource inputs might actually be *essential* to production, although the quantities needed might be virtually infinitesimal [e.g. Dasgupta & Heal 1974, 1979].

The use of C-D production functions allowed the modelers to arrive at a very interesting counterintuitive result, *viz.* that economic growth can continue indefinitely even without external resource inputs, if only the elasticity of substitution of capital for resources is sufficiently large. In other words, the conclusion of Solow, Stiglitz *et al*, that natural resources are unnecessary to growth, follows from the capacity for *creatio ex nihilo* noted by Christensen & Fritz. One rather harsh critic called it "a conjuring trick" [Georgescu-Roegen 1979]. Fundamentally, however, it was the casual use of an oversimplified, physically unrealistic production function to derive important conclusions about the real world that Georgescu-Roegen objected to. (Regrettably, his legitimate criticisms were never answered, or even acknowledged, by the neoclassicists.)

One other theoretical paper from the 1970s deserves special mention because it avoids this conceptual problem [d'Arge & Kogiku 1973]. In this paper, an unspecified homogeneous production function of the first degree is also assumed to permit substitution between labor and resource consumption. However the authors explicitly require that both production and consumption are essentially material in nature. They also postulate a finite natural resource stock, introduce material waste (and pollution) and insist on the conservation of mass. The paper then derives optimal consumption paths over time, under various other assumptions, including the possibility of recycling. The A-K analysis, incidentally, does *not* conclude that economic growth can continue indefinitely. On the contrary, not only growth but consumption itself ends when the resources are exhausted, prompting the rubric "cake-eating" problem. Under some assumptions with regard to time preference consumption of material goods actually rises over time in the d'Arge-Kogiku model (before the final crash, of course) to compensate for the welfare losses due to rising levels of pollution. In any case the behavior predicted by the A-K model is in sharp contrast to that predicted by Solow's C-D model.

Later some simple models of the Solow type were modified for use in energy policy analysis by adding an explicit resource (energy) input term: an explicit production function (usually Cobb-Douglas) was chosen *ad hoc*, and the exponents of the factors were estimated econometrically [Allen *et al* 1976; Allen 1979; Hannon & Joyce 1981].

Problems arise with the econometric approach to parametrization, due to the unavoidable interdependence of labor, capital and energy flows. There is an enormous literature covering numerous early efforts to sort out these interrelationships statistically, but no great insights have emerged [e.g. Kennedy & Thirlwall 1972]. One more recent study is worthy of mention. Using data from the years 1929, 1940, 1941 and 1947–1969, but otherwise with essentially the same model specifications as Solow, Hannon & Joyce [*ibid*] obtained significantly different results. Among other differences, the econometric fit yielded a technical progress growth rate of 1.38% per annum, slightly less than the 1.5% per annum found by Solow.[12]

Returning to the C-D and CES functions and the "natural" interpretation of marginal productivities as payments to factors in the national accounts, one might ask: Where are the payments to natural resources (or natural capital)? The answer to this question is has two parts. There are actual payments to owners of mines and forests, but these payments (rents) are typically lumped with other payments to capital or labor. But there are no rents (except user fees, which are often negligible or non-existent) paid to common property owners, especially where the common property is intrinsically indivisible — as in the case of biodiversity, clean air, scenic beauty or the climate. This does not mean that natural capital is not a true factor of production. It merely means that the market system is imperfect and the interpretation of marginal productivities as "shares" is unjustified. In fact, some factors are unpaid, or underpaid. In other cases the payments are disguised and/or appropriated by other factors [e.g. Blanchflower *et al* 1996; Van Reenen 1996].

Since the "limits to growth" controversy of the 1970s it has been widely accepted that resource flows should somehow be incorporated into production functions. Cobb-Douglas and CES production functions are inappropriate because of their built-in assumption of constant elasticity of substitution. A more flexible approach has been possible with the introduction of the generalized transcendental-logarithmic (translog) production (or cost) functions, introduced in the early 1970s by Dale Jorgenson and his associates.[13]

One version of the Jorgenson approach is to postulate a special form of cost function of total output Q, factor prices P_K, P_L, P_E, P_M, and time t, viz. $C(Q, P_K, P_L, P_E, P_M, t)$. This assumed cost function is, essentially, a quadratic function of the logarithms of the factors (except for time), so it resembles the first two terms of a generalized Taylor series expansion. On differentiating C logarithmically with respect to the prices, and normally with respect to time, one obtains a set of five linear equations in factor prices and time. (If electricity is introduced as an additional factor of production, the number of equations is increased to six.) The first four are cost elasticities (or cost shares), analogous to price elasticities, with respect to logarithms of factor prices. The negative reciprocal of the cost elasticity with respect to time can be interpreted as the aggregate rate of disembodied technical change.

All the coefficients in the five sets of equations are assumed to be constants, to be determined econometrically. The coefficients of the logarithms of the four factor prices in this equation are interpreted as the *biases* of technical change with respect to the factors. To be sure, the generalized translog production (cost) function permits some of the coefficients of cross terms to be negative, implying that the corresponding factors are complements rather than substitutes. This is a step towards realism and a major virtue of the translog formulation. It is extremely difficult, however, to imagine that all these cost or price elasticities truly remain constant over time, given the radical changes in technology that have occurred in the past, and are likely to occur in the future.

The translog production function, with energy as a factor, was first applied to multisectoral models in the early 1970s [Berndt & Jorgenson 1973; Berndt & Wood 1975], mainly in the context of assessing the impact of price changes. The role of energy in economic growth over a longer time period (1958–1979) has also been studied by Jorgenson, using a 35 sector model of the U.S. economy and 5 factor inputs (including both electrical and non-electric energy) [Jorgenson 1984]. In this study Jorgenson focussed explicitly on the question of bias, raised above. He concluded, among other things, that technical change is highly variable in terms of factor biases, from one sector to another. It is capital using in some sectors, capital saving in others; labor using in some sectors, labor saving in others, energy using in some sectors, energy saving in others. A more particular result was that econometric estimation of the bias coefficient for energy vs. time, based on recent history, implies that rising energy prices tend to reduce the rate of economic growth. This conclusion seems to fit the preconceptions of most economists.

However, econometric results of this kind are very sensitive to the model specification and the time period selected for calibration. In this context, recent empirical and still unpublished work [Oravetz & Dowlatabadi 1996] is relevant. This work was addressed to the question of whether it is realistic for modelers to assume a constant drift (i.e. bias) toward increasing energy use efficiency in the absence of price or policy signals. Such a bias has been explicitly assumed, for instance, by many economists and modelers interested in long term climate policy issues [e.g. Edmonds & Reilly 1985a,b; Manne & Richels 1992; Burniaux *et al* 1992; Nordhaus 1992]. The parameter in question is now usually called autonomous energy efficiency improvement (AEEI). The standard procedure has been first to choose an aggregate price elasticity from the literature, then to determine the impact of price changes on historical energy consumption for that choice of elasticity and model structure (by backcasting), and finally choose the "best" value of AEEI as a residual. The Energy Modelling Forum (EMF) has formally adopted this procedure to facilitate modelling comparisons. AEEI is typically given values ranging from 0.5% to 1.5% per annum. As might be expected, long term forecasting results are highly sensitive to this choice.

To avoid having to select an elasticity arbitrarily and produce a more robust result Oravetz & Dowlatabadi [ibid] undertook a major elaboration of the previous approach to determining AEEI.[14] To make a fairly long story short, they got considerably better fits than other models. An AEEI value of -1.6% per annum was found to be best suited to replicate the trend from 1954–1974, when energy prices were declining, while an AEEI value of +1.6% per annum was best suited for replicating the subsequent 20-year trend when prices were more volatile. Taking both periods together the best value of the parameter turned out to be +0.17% per annum. In fact, the AEEI parameter itself appears to be policy sensitive, and price sensitive. Changes in the trend can apparently be initiated by strong price signals, as occurred in 1973–1974, although the new trend itself may persist long afterwards.

The obvious conclusion from this work is that one cannot extrapolate AEEI for a hundred years into the future. But, at a deeper level, the point is that calibration parameters really do depend on the choice of time periods for fitting. This might seem unremarkable at first. But, if it were true that production depends only on factor inputs and time (as in Solow type models), or on factor prices and time (as in the Jorgenson models), then the choice of time period for model calibration should not matter. To put it another way, if those structural assumptions were true it would imply that there exists a set of constant technical bias parameters discoverable by econometric fitting. Evidently this notion is fundamentally misconceived. (This means, incidentally, that the claim by Hogan and Jorgenson to have endogenized technical change cannot be taken seriously).

To summarize: resource flows (or a suitable proxy) are indeed a factor of production. But to introduce resource flows in a simple production function of the C-D or CES type, permitting unlimited substitution with constant elasticity of substitution between factors, creates insurmountable conceptual difficulties. A more flexible (and probably more complex) production function is clearly needed. On the other hand, the Jorgenson model is almost too complex, but it is still inflexible in the technological dimension. It assumes, in effect, that technological change is entirely attributable to price changes, which is hardly defensible in the long run.

To proceed, I propose to consider introduce the `meta' model promised earlier. It is explicitly constructed from two limiting cases. These are derived from a thirty year old conceptual dichotomy from Kenneth Boulding, contrasting the "cowboy economy" in which (most) natural resources are a free good, *vis a vis* the future "spaceship economy" in which natural resources are limited [Boulding 1966].[15]

The Cowboy Economy

Consider the "cowboy" economy first. It is clearly modelled on the early to mid-19th century trans-Appalachian U.S. farming/ranching society — a world in which labor and capital were very scarce and costly but natural environmental resources (especially arable land, grazing, water, game and wood for fuel or construction) were plentiful. Even mineral resources, such as stone, gravel, and clay for bricks or pottery, were often free for the taking. Most people lived on small self-sufficient farms. The pioneers built their own houses, grew their own food and made their own clothes. Their animals reproduced themselves. Only labor, metal goods — mainly tools and utensils — and capital were scarce.

Traded goods in the cowboy economy were either self-propelled (i.e. livestock) or portable and readily protected from spoilage, rot, decay or attack by insects or rodents. Live animals were undoubtedly the first trade goods, followed by grain and preserved foods (dried, salted, smoked, fermented or pickled), oils and fats, wine, leather, furs, fibers and fabrics (wool, cotton, linen, silk, hemp, jute), wood and wood products, specialized plant products like coffee, tea, sugar, herbs, spices, perfumes and pigments, forged metal items and metal tools, weapons, and ceramics. This list still described most trade goods for most of the world until the 19th century. Only after the development of steam power, using coal as a fuel, did the list of traded goods expand significantly, to include complex manufactured products like guns, clocks and watches, sewing machines, shoes and clothes, bicycles and so on. And only in cities and towns was there a "labor market" where people sold their labor for money to buy goods. (Thanks to the guild system under various names, even the urban labor market was hardly competitive anywhere, except in the case of disorganized unskilled rural labor driven off the land and into the growing factory cities of western Europe).

By now half the world's population lives in towns and cities, and the monetary economy has spread even to rural areas of the developing countries. What remains of the self-sufficient rural village barter and do-it-yourself economy of the past seems to be almost negligible in economic terms — at least, if rural unskilled labor is valued at it's marginal wage rate. But, the economy of today is still largely based on "throughput": raw materials are extracted, processed into intermediates and final goods, and finally discarded. This processing and distribution system is driven by mechanical power obtained mainly from fossil fuels. Many intermediates — especially fuels and additives, lubricants, solvents, soap and detergents, bleaches, paints and dyes, and paper and packaging materials — are used only once, and in a way that results in the dispersion of their material substance into the environment in such a way that recovery and recycling are impossible. Moreover, thanks to efficient long distance transport, trade in portable goods is growing much faster than total economic output. This means that even potentially re-usable and re-manufacturable products are increasingly being used and discarded a long distance from where they were produced.

What does this economic evolution imply about the production function? At first, land was not scarce, but produced capital (such as horses, cattle, farm implements, houses and furniture) were quite easily produced from raw materials, by the application of human labor. Capital, on the other hand, — especially horses and horse-drawn tillers, harvesters, etc. — reduced the need for labor. Thus the substitutability, scarcity, and essentiality criteria were all met. The traditional C-D or CES production functions, with labor and capital as factors, would seem to be a very reasonable approximation for a true cowboy economy. Note that, since natural resources were not scarce and can be ignored in this case, the two factors can safely be considered to be abstract aggregates for which the law of conservation of mass does not apply. Thus there is no inherent inconsistency.

The Transitional (Throughput) Economy

In the transitional economy that began with the industrial revolution, human labor has changed it's role. Notwithstanding the fact that some "John Henry" jobs requiring physical strength still remain,[16] most workers no longer do much "work", in the thermodynamic sense (exerting force to overcome resistance over time). For most people, work is essentially tool or raw material manipulation, machine control and/or supervision, information transfer, or supervision of other humans who perform these functions. A few of the machines are very complex and require a high degree of skill to control. (Driving a car or truck through traffic would be an example.) But, thanks to electronic sensors and information processors, more and more of the machines that do production tasks can perform most of their functions without direct human intervention. The only real role of humans in more and more situations is to feed the machine, read dials, push buttons and call for assistance whenever there is a problem. Even the machine feeding task is becoming mechanized.

It is said that skills are scarce. But employment opportunities seem to be shrinking even for highly educated people, such as scientists. In this economy, it is unclear whether labor is truly a factor of production, at least to the extent that population or "the labor force" would constitute a reasonable proxy. It is plausible that capital, labor, energy (exergy) and materials are all factors of production; this combination is typically denoted KLEM. It is even arguable that electric power should be taken as a distinct factor by itself, as was done by Jorgenson and his associates [*op cit*]. If one were forced to choose two factors only, commercial exergy — including material inputs of all kinds — would probably have to be one, and aggregate capital might be the other. But, to use a Cobb-Douglas or CES production function with capital and labor plus energy and/or materials as additional factors would also implicitly permit the production of material goods from immaterial inputs. This violates the basic laws of physics, as commented earlier.

The Spaceship Economy

Now consider the contrasting case of a sustainable steady-state economy in a future "space ship" world. It can be argued that there is no limit *in principle* to the economic service output that can be obtained from a given physical resource input [e.g. Ayres 1978; Ayres &

Kneese 1989]. Another way of saying the same thing is that there is no limit *in principle* to the degree of dematerialization, reconditioning, remanufacturing and recycling that can be achieved in the very long run. One must hasten to add that this does not mean that no physical materials need be processed at all. Nor does it imply that recovery, remanufacturing and recycling can be 100% efficient. No such claim need be made. It is enough to assert, simply, that nobody can define a finite absolute minimum material input requirement to produce a unit of economic welfare, with the obvious exception of food and drink. This conclusion is evidently in agreement with Solow, Stiglitz, *et al* [op cit].

Let us assume that this sustainable steady state "spaceship" society is wealthy, with a constant population, and thus a constant (or declining) labor force. The spaceship analogy implies that most non-renewable materials, such as metals, are recycled, although such an economy may extract and process some bulky virgin materials for construction purposes. This hypothetical economy must generate far more welfare (i.e. use value) from each kilogram of material processed than our current economy. It must, in short, be essentially service based. In contrast to our present economy, which is extremely material intensive, this hypothetical future economy will mostly utilize renewable forms of energy — especially solar electricity, solar hydrogen, hydropower and biomass — and it will re-use, recondition, remanufacture and recycle most intrinsically scarce materials many times. To do so, this economy will require produced capital equipment, which will also be periodically reconditioned, remanufactured, etc. This capital equipment will depreciate, of course, but depreciation through wear and tear will presumably be compensated by continuous improvement in terms of design and performance.

The physical stock of produced capital for this sustainable spaceship economy of the future will have two functions. First it will constitute the physical *framework* — "skeleton and skin" — of the social organism. (This includes buildings and infrastructure). Since the population is presumed to be stable, it is reasonable to assume that the physical magnitude of the "skeleton and skin" no longer increases beyond a certain point, thanks to declining marginal utility. The second function of the future physical capital stock is to produce whatever is needed to repair, maintain and upgrade, both the framework, and the materials processing system, using renewable energy and renewable or recycled materials. This function can be characterized as "industrial metabolism" [Ayres 1989b].

Most industrial metabolic activity in the spaceship economy will necessarily be for maintenance purposes. However, thanks to continuing learning and technological progress, use-value can also be added. Whenever an item of physical capital is reconditioned or replaced, it can also be improved in terms of performance, durability, aesthetics. In effect, the service output of the capital can be increased without limit. Thus, economic growth is still possible in this economy, but it must arise from (1) improving the quality of capital goods and (2) improving the quality of consumer services. Quality, in this formulation, can be characterized as technology level, or information content.

In this hypothetical world the only scarce resources would be knowledge or technology, common property environmental resources (such as biodiversity, scenic beauty, climate, etc.) and solar energy. There would be some payments to "labor" (i.e. to individuals) but actually these payments would — even more than now — reflect scarce skills and knowledge embodied in labor, not labor hours. It is more realistic to think of these as payments to technology or knowledge. There will also be payments to physical capital, as at present, but they will reflect costs of maintenance and improvement (reflecting R&D expenditure), not scarcity rents. They will, in any case, be intermediates. There may be monopoly profits, either to organized labor or to cartelized firms, but this would depend on the social organization. There would be no payments to natural capital in the sense of scarcity rents to owners, but there will be costs of maintenance for natural systems.

A production function with two factors (resource flows and "capital") might describe such an economy. Capital, in this case, would be interpreted as some combination of information embodied in physical structures and equipment, plus human capital (managerial and design skills, and "know how"), and disembodied ("free floating") knowledge recorded in books or computers. The information embodied in physical capital is analogous to genetic information, in the case of living organisms, while the information pertaining to design, organization, management and operation is analogous to "brain information" for living organisms. Taking this analogy a step further, it is plausible that brain information will increasingly dominate over genetic information — as it does in the biological case. However, this speculation need not be pursued here.

A Generalized Production Function

A natural implication of the argument presented above is that a generalized production function should reduce to the "cowboy" case in one limit and to the "spaceship" case in the other. A linear combination of the form

$$F = (1 - A)F^1 + AF^2 \qquad 0 < A < 1 \qquad (1)$$

where A(z) is some monotonically increasing function of an argument z discussed below. The functions F^1 and F^2 are discussed later.

The form of A(z) must be an elongated S-curve, rising slowly at first, then more rapidly, and again more and more slowly is it approaches the upper limit of unity. If the argument z(t) is already of this form (at least it is monotonically increasing and always less than unity) the simplest form for A(z) is then of the form

$$A(z) = z^n \qquad (2)$$

where the exponent n is chosen econometrically. The determination of n is best left until after z(t) itself is quantified. (It will be seen later that $z << 1$, whence $n << 1$). The most natural procedure will be to select the value of n which best matches recent rates of growth.

Since we want to endogenize technological change, and therefore to eliminate time as an explicit variable, we now seek a suitable proxy for the state of technology z. A number of possibilities have been considered. Expenditure on R&D, and on education, have been proposed as possible measures of investment in knowledge, but they do not provide much help in estimating knowledge stocks. Alternatively, one might plausibly measure the state of technology in terms of the number of patents issued, or the number of technical journals in existence, or even the number of books in print. In the future "spaceship" earth, all of this information will probably be stored in computer memories. In that case, the available memory capacity and the information transmission/processing capacity would be possible proxies. However most of these — and some others that have been proposed — are measures of only one type of knowledge, namely the "free floating" type that was mentioned above.

What can be suggested as a proxy for information embodied in structures, organizations and skills? This is a deeper and more difficult question. The answer proposed here is that a reasonably good proxy for the state of technology z(t) at any given time is *technical efficiency*, defined as the efficiency with which "raw" exergy from inanimate sources or animals is converted into final services. This, in turn, can be decomposed into a product of two subsidiary ratios, as follows:

$$z = uv \tag{3}$$

The first factor u is the *exergy delivery efficiency*. This is the ratio of delivered exergy — meaning electric power, space heat, process heat (or steam), or mechanical work delivered to a driveshaft — to the exergy embodied in fuels, animal feeds, or hydraulic energy inputs. The second term in (3), namely v, is the *service delivery efficiency*. It is the ratio of final service output to delivered exergy or work input, as defined above. The first of these ratios can be estimated with fair accuracy by extrapolation from available energy statistics and technical analysis. The second term involves somewhat more qualitative and cruder — but feasible — estimates, as will be seen. In both cases, the estimates can be made at the sectoral level. For a rough quantitative approximation to z, see *Appendix A*.

The variable z is also, in essence, a measure of the productivity of resources. In the first place, the efficiency of conversion of raw exergy inputs into final service outputs is obviously dependent on technological capacities in virtually every field of activity, from metallurgy and materials science to electrical and electronic engineering. It reflects progress in the technology of material processing and manufacturing, insofar as finished materials (such as steel and plastics) are being produced more efficiently from raw materials. In the second place, finished products are similarly producing more and more "performance" in the broad sense — taking into account all the attributes contributing to consumer satisfaction — from fewer material inputs. This applies to housing, household management and transportation as well as telecommunications and entertainment. Electrification and chemistry were the major drivers of dematerialization in the late 19th century. Microelectronics, digital information processing, and biotechnology are the major engines of dematerialization today. Dematerialization is, of course, the obverse of materials productivity.

As noted previously, it is not unreasonable to retain the conventional two factor (capital K and labor L) production function for the "cowboy" case, even in the simple Cobb-Douglas form. The other limiting "spaceship" case can also be characterized by two factors, namely capital K^* and resource (exergy) inputs R. I have used the asterisk to alert the reader to an important *caveat*. While capital in both the cowboy and spaceship economies can be conceptualized in the same way (i.e. as incorporating knowledge, organization and skills, as well as tangible reproducible capital) it is not necessarily measurable by the same proxy as capital in the cowboy economy. Thus it might be safer to use a different symbol H to distinguish human capital for the spaceship case. This is consistent with the approach of the so-called "new" growth theorists [e.g. Romer 1990].

One of the clear implications of the previous discussion of limiting cases is that the common assumption of constant elasticities of substitution between capital and labor *over time* is inappropriate and must be discarded. (The fact that the elasticity of substitution between energy and labor or capital cannot be constant, as has already been noted.) Both labor and capital change their nature and become less material intensive (physical) and more information intensive as the economy evolves from the cowboy stage to the spaceship stage. In the long run labor and tangible physical capital will inevitably become less scarce, or — in the case of unskilled labor — not scarce at all. Their ability to command scarcity rents will therefore decline, except insofar as they can be preserved by cartelization (e.g. labor unions).[17] The composite production function proposed in (1) obviously meets this condition.

Another condition we need to satisfy is the qualitative one imposed by the Kuznets inverted U. During the "cowboy" phase of industrialization (when resources are not scarce) it is plausible that exergy resource consumption should increase faster than GNP. During the "spaceship" phase, by contrast, exergy is the scarcest factor. Thus it is plausible that technological progress should continuously reduce exergy consumption per unit of GNP. Both of these limiting cases are consistent with the Kuznets inverted U.

Scarcity and Marginal Productivity

The simplistic traditional approach to estimating the marginal productivity of an input has been to equate it with payments to that input in the national accounts (assuming equilibrium conditions, of course). Evidently non-renewable materials and "natural capital" are becoming scarcer and will become increasingly scarce in the future as we approach the "spaceship" phase. Yet, solar energy and some of the most critical environmental inputs to the economic system — such as climate and biodiversity — are inherently common property resources. Can scarcity rents be defined in such a case?

The classic argument that has been made is that increasing resource scarcity should be reflected by rising prices [e.g. Hotelling 1931]. But historical commodity price trends show no such increase. It would appear that progress in the technologies of resource discovery, extraction and concentration has more than compensated for the gradual exhaustion of most natural resource stocks (the primary exception being timber) since consistent price data became available in the mid 19th century [Barnett & Morse 1962]. This trend of declining commodity prices has continued at least through the 1970s [Smith 1979] and very likely since.

There are three problems with depending on this line of argument. First, common property environmental resources mentioned above are unpriced and were not included in the Barnett & Morse analysis. But other indications strongly suggest increasing scarcity. For instance, the use of petroleum fuels generates combustion effluents, such as carbon dioxide, sulfur dioxide, nitrogen oxides, carbon monoxide, particulates (smoke), and so on. Carbon dioxide contributes to climate warming, which may be quite harmful to the environment. Fuel-bound sulfur and nitrogen oxides produced in high temperature combustion processes both contribute to acid rain. Particulates are very harmful to human health. The exact numbers don't matter here. The point is that — as economists consistently argue — when the use of a resource causes harm, the damage cost should be internalized i.e. reflected in the price of that resource in order to arrive at the optimum level of use.

Yet, environmental and health damage costs due to fuel combustion are currently not reflected in market prices of fuels, as is well known. These costs are not paid explicitly, either by resource extractors or by final users. In short, resources are used to excess because they are much too cheap. In the case of hydrocarbon fuels (and possibly other resources such as heavy metals), the environmental damages resulting from use could outweigh the market prices of those resources several fold [e.g. Ayres & Walter 1991]. Several studies have estimated the marginal cost of avoiding a buildup of atmospheric CO_2 to reduce future damages from climate warming to be in the range of \$50–\$200 per metric ton (MT) of carbon. For instance, to cut emissions to 80% of 1990 levels (not enough to stop climate warming) could be accomplished by a gradually phased in tax of \$60 per metric ton of carbon [Jorgenson & Wilcoxen 1990].

A recent summary of recent literature estimated the following marginal damages in 1987 dollars per metric ton of airborne emissions [Repetto *et al* 1996]. It is summarized in *Table 1*. While one metric ton of fuel consumed in a modern power plant, industrial boiler or automotive vehicle generates only a few kilograms of airborne emissions (except CO_2), it is obvious that the damages can easily outweigh the fuel costs.

Table I: Damage Costs from Hydrocarbon Combustion

	Damages per metric ton ($)	*Metric tons per trillion BTU*	*Total damages per trillion BTU*
Carbon dioxide (CO_2)	20 50	80 483 80 483	1 609 660 4 024 150
Carbon monoxide (CO)	1	1 771.4	1 771
Nitrogen oxides (NO_X)	841	348.9	293 427
Sulfur oxides (SO_X)	964	91.6	88 281
Particulates (TSP)	3 192	55.5	177 079
Volatile organic compounds (VOC)	1 460	256.9	375 103
Lead (Pb)	1 384	0.6	819

The second reason for caution is that the conventional GDP measure of output makes no allowance for resource depletion. In particular, it still treats the sale of natural resources as income, without making any corresponding subtraction for the depreciation of natural resource capital stock [e.g. Repetto *et al* 1996].

Third, the cost of replacement (of exhausted sources of non-renewables) should be taken into account. Unlike manmade capital, natural resources cannot necessarily always be replaced at the cost of locating and exploiting the original resource, notwithstanding the long history of declining resource prices noted above. At some point the rate of technological improvement — returns to investment — applied to natural resource discovery and recovery will inevitably begin to decline, if the pattern that has been observed in other areas of technology is repeated in this case. On the other hand, as consumption increases the rate of decline of the grade of resources being extracted currently is likely to accelerate. This has certainly happened in the case of renewable resources such as forests and fisheries.

For example, a marginal barrel of oil from Saudi Arabia today may have cost $10 or less to find and pump in terms of current dollars. But, barring the unlikely discovery of a new (and accessible) oil territory comparable in magnitude to the Persian Gulf, the replacement marginal barrel of oil from deep under the Gulf of Mexico, or from northern Siberia, might cost $30 or more to find and extract. And the replacement costs keep rising. It seems clear that to value resource stocks and depletion at current average market prices is seriously misleading.

In summary, even though the *apparent* costs of natural resources only amount to a few percent of GDP for an advanced industrial economy, these figures are seriously underestimated. What all this implies is that, even in the last century, and at present, fossil exergy — and, for that matter, renewable exergy from the sun — constitute a factor of production as important as physical capital. Both are produced by human labor, together with capital and exergy. In short, labor, capital and exergy are cofactors. The technical detail of correctly accounting for the exergy share of production is not something that needs to be discussed further here.

It is clear from many sorts of evidence that much of the historical increase of technical progress (or labor productivity) that apparently drives economic growth is, in fact, attributable to the increased exergy flux, per unit of human labor, that was supplied from outside the system. In effect, exergy (in combination with machines, i.e. capital) has been a substitute for human labor in many sectors. (Machines, alone, clearly cannot replace human labor.) If one adds exergy to the production function, then economic output — and growth — must be reallocated among three factors, labor, capital and exergy. This reallocation, in turn, would surely explain a much larger fraction of total historical growth, leaving correspondingly less to be explained by exogenous Solow-type multipliers.

In summary, since the market system is imperfect, and since labor and capital markets are not really in equilibrium, it is inappropriate to argue that observed payments to labor or payments to capital (the only two categories in the national accounts) can be simply equated to marginal productivities. In fact, labor markets are certainly distorted by both regulation and cartelization, undermining the equilibrium assumption. It is therefore perfectly reasonable to assume that other factors — notably natural capital — have marginal productivities, even though they receive no explicit "payments". Of course, it follows that one must seek some other (presumably econometric) method of estimating marginal productivities.

Implications

In the present paper two modifications of the standard KLEM production function formulation at the macroeconomic level are proposed: a simplification and an elaboration. The simplification is to recombine the energy and materials services (E and M) as a single variable X for *exergy*.[18] This simplification is justified by the laws of thermodynamics, as was explained in the text. Of course it significantly reduces the number of parameters to be determined.

The elaboration is to reformulate the function as a linear combination of the form shown in Equation (1), viz. $F = [1 - A(z)]\,F^1(K, L) + A(z)F^2(X)$. To implement this approach in practice it is necessary to define and estimate $z(t)$ *and* $A(z)$ and to develop time series for X. A crude estimate of $z(t)$ for the U.S. from 1800 to the present is provided in *Appendix A*. The simplest form for $A(z)$ is the exponential (equation 2). For forecasting purposes it would be necessary to determine the best value for n econometrically. To fully endogenize the model, of course, it would also be necessary to incorporate an explicit link between current economic activity (including R&D) and changes in z.

This approach may appear, at first, to be *ad hoc* and therefore potentially inconsistent with the traditional insistence on starting from neoclassical micro-foundations. However, it is well known that the so-called micro-foundations (perfect markets, perfect information, utility maximization and profit maximization) are themselves inconsistent with reality [e.g. Nelson 1997]. In the real world rationality is bounded. Markets are inefficient. Competition is imperfect. Firms do not necessarily operate on the efficiency frontier. Information is costly and it does not propagate instantaneously. Profits arise from information asymmetries. The future is uncertain.

In short, the paper argues that the traditional micro-foundations — notably the assumption of growth-in-equilibrium — are themselves both inconsistent and unnecessary. Nevertheless, the new formulation is consistent with the standard neoclassical formulation where the latter is clearly applicable (i.e. in the limiting "cowboy" case).

Appendix A: Technological Progress as Exergy Conversion Efficiency

To calculate an overall technical efficiency (equation (3) in the text) we need to aggregate over all the different exergy sources and conversion pathways to final services. The first step is to estimate historical energy consumption *per se*.

Total energy statistics can be divided into two main categories, namely thermal energy from fuel used as such (for space heating, water heating, cooking, and metallurgical operations) and non-thermal energy used initially as mechanical work. The latter includes work done by animals, water power, wind power and heat engines. Electric power, up to very recently, has been produced only from generators driven by mechanical power, either from hydraulic sources or heat engines. This will change in the future, however, thanks to the introduction of direct conversion via photovoltaic (PV) cells. Electric power, however, can be regarded for our purposes as the purest form of mechanical work, since it can be converted directly into work — by an electric motor — with little or no loss.

The classification problem is somewhat confused by the fact that electricity can also be converted into heat, as in a resistance heater (such as an electric furnace or water heater) or a microwave oven. The situation is even further confused by the use of mechanical power to "pump" heat from one reservoir to another — without actually producing or destroying it — as in a refrigerator, air conditioner or heat pump. However all of these are developments of the present century. During the first two thirds of the 19th century, thermal energy was used almost only for household purposes, with iron and steel and other industrial uses of heat becoming significant only towards the end of the period.

A scattering of quantitative estimates is available from 1850 on, but reasonable extrapolations can be made to back to 1800. In 1850 heat energy from firewood alone was estimated at 2,140 trillion BTU, mostly for households [Schurr & Netschert 1960, Tables 1 & 2]. Thus, firewood was by far the dominant source of energy for household purposes. Per capita use was not changing rapidly. Thus, it seems safe to extrapolate aggregate firewood use back to 1800, simply in proportion to population. On that basis, aggregate firewood use in 1800 must have been close to 490 trillion BTU.

In colonial times most mechanical work not done by humans was done by horses and mules, supplemented by water mills and windmills. There are no data on livestock prior to 1867. In that year there were 6.8 million horses and 1 million mules, mainly on (approximately) 2.4 million farms, or roughly three animals per farm. Rural population for 1880 was 36 million, of which 60% (22 million) lived on 4 million farms, or 5.5 persons per farm. In 1800 the total population of the country was 5.3 million, of which 5 million were classed as "rural". One can probably assume that about 60% (3 million) were farmers, living on roughly 550,000 farms at that time. Using these ratios, one can estimate the horse/mule population in 1800 to have been about 1.7 million. In 1850 it is likely that the working animal population was around 5.4 million.

Assuming each animal produced 1000 hp-hrs per year, this would imply 1.7 billion hp-hr in 1800 and 5.4 billion hp-hr in 1850.[19] The number of horses and mules in service combined reached 20 million in 1900, peaked at about 26 million between 1914 and 1920, and only declined slowly thereafter (to 15 million in 1938 and 10 million in 1947), as tractors and other equipment driven by internal combustion engines increasingly took over farm work.

As noted, horses and mules were mainly used on farms, but as many as one third, in the 19th century, were probably used for transportation purposes. (There are no firm data on this, however).

Mechanical work done by inanimate power sources in 1850 has been estimated at 2.7 billion hp-hr, of which 52% was windpower, 33% waterpower and 15% steam power (@1.1%

efficiency) [Dewhurst 1955]. Windpower was almost exclusively used in agriculture (for water pumping and grinding of grain). Water power, on the other hand, was entirely used for driving machines — mainly in the textile industry. Extrapolating back to 1800, it would appear that total work done (mainly by water power) must have been of the order of 0.5 billion hp-hr. Energy consumed by industry prior to the 1860s or so consisted of hydraulic power — most of which was used by mills of various kinds — and some charcoal and, later, coal, used for iron smelting and forging purposes. The composition of mechanical power sources was changing rapidly. By 1870, the total output had risen to 5.8 billion hp-hr, or of which the water share had fallen to 29% and the steam share had risen to 52%. Wind power use for irrigation (on prairie farms) had peaked in 1860 at 2.1 billion hp-hr (48% of the total) but had a decade later it had already declined sharply to below the 1850 level. In any case, animals were by far the dominant source of mechanical power in the U.S. 1867. It was only long after 1900 that the role of animals as a power source declined significantly.

As late as 1870 three quarters of U.S. energy consumption (not counting animal power) was still supplied by wood [Schurr & Netschert 1960], mostly still for home heating. In 1879 only 4.5% of wood fuel was used in the form of charcoal used for iron making [*ibid* p. 53]. By the end of the 19th century horses were being phased out of transport applications and coal burning steam engines were the prime movers for railroads, ships, factories and electric power plants. Today, steam or water turbines still supply electric power while internal combustion engines supply power for mobile applications. Heat and light were supplied by direct combustion until the electric light arrived on the scene around 1880 and since then electricity has steadily increased its share.

Table A-I: Energy Share Allocation, by Year: (% of National Total)

Category	1800	1850	1900(1)	1940	1960(2)	1979(3)
Space heat	89	85	40	25	18.5	13.3
A/C & refrigeration	na	na	na	2	3.7	6
Cooking & washing	a)	a)	5	5	5.5	5.7
Lighting	1	1	2	2	2	4
Farming & construction	5	5.6	8	6	6	6
Transport drive(b)	3	3.8	10	20	25	25
Machine drive(c)	1	1.5	5	6	7.4	8
Industrial	1	3	25	30	26	20
Other(inc. feedstock)	na	na	3	4	5.9	12

(a) *included in space heat category (row 1) for 1800 and 1850*
(b) *assuming one third of working animals used for transportation purposes*
(c) *not including machines producing electric power*
(d) *included in category "Industry"*
(1) *except as discussed in the text, data in this column is estimated by the author*
(2) *data in this column is largely taken from [Hirst & Moyers 1973]*
(3) *data in this column is largely taken from [Ayres 1989a]*

A rough breakdown of national energy use since 1800 can be constructed, as shown in *Table A-I*. A fairly detailed breakdown by use was available from the Census Bureau for 1970 and 1979. (Later these compilations were dropped, due to federal budget cuts). I have interpolated the figures for 1900 and 1940, although historical research could doubtless refine and improve my guesses. The figures for 1850 are largely derivable from the two main sources cited above, as discussed in the text. Note that the rapidly growing "other" category includes petrochemical feedstocks, as well as a host of minor applications of electricity, including small appliances, radios, TVs, battery chargers, telecommunications, computers, xerox copiers, radar, X-ray machines, electrostatic smoke control devices, electrostatic printers, and so on.

Conversion Efficiency

In the case of fuels used to produce space heat, the conversion efficiency is the ratio of heat radiated or convected into the space to be heated to the total heat generated by the combustion process. In 1800, and still in 1850, most wood was burned in large fireplaces, not stoves, to avoid the extra labor needed to chop the wood into stove sized pieces [Schurr & Netschert 1960, p.50]. Since the fuel was essentially free, there was no economic incentive to use it efficiently. In fact, it was used extremely inefficiently. Most of the heat generated in a large fireplace is carried up the chimney. The thermal efficiency of heating by this method was about 8% in 1850 (and probably about the same in 1800 . Thanks to the introduction of wood stoves, then central heating and better insulation, this measure of efficiency had reached 60% by 1955 [Schurr & Netschert 1960 p. 49] and probably 70% by 1979.[20]

It is difficult to make exact comparisons between animals and machines in terms of thermodynamic efficiency, but a rough estimate for humans suggests that the efficiency is about 10%.[21] (Heat engines did not reach this level of efficiency until well into the 20th century.) In terms of the unit more commonly used by energy analysts in the U.S., one million horses or mules produce 2.54 trillion BTU/yr of "useful work", while consuming about 25.4 trillion BTU/yr in feed. Thus the feed equivalent of working animals on farms in 1800 must have been around 43 trillion BTU, with an uncertainty of 10% or so. For 1850 the feed consumption (for 5.4 million animals) was about 137 trillion BTU. By 1900 it had reached 508 trillion BTU, for 20 million animals; it peaked at 650 trillion BTU in 1918.

Steam engines were used mostly by railroads and riverboats before 1850; they were only installed for factories where water power was unavailable, as in seaports such as Baltimore, Philadelphia and New York. In 1850 the average efficiency of steam power, in terms of power delivered to the wheels of a locomotive (or a loom) by a drive shaft, was calculated to be 1.1%; it rose gradually to 1.8% by 1870, 3% in 1900 and 7% in 1920 [Dewhurst 1955]. These figures reflect the large number of small and inefficient engines in use. Large steam engines used for producing electric power, starting in the late 1880s, were more efficient, albeit seldom more than 10%. As high pressure steam turbines were introduced after the turn of the century, however, large central units became far more efficient than smaller engines. The most advanced single cycle thermal power plants of today operate at 45% efficiency (including the generator) and combined cycle plants can do better still.

Wind power (from stand alone windmills) enjoyed a brief period of popularity during the middle of the last century, especially between 1850 and 1870. The efficiency of these machines at converting wind energy to mechanical power has been estimated at 18% [Dewhurst 1955].[22] I think this is probably too high, but I have no better estimate. Modern windmills, using light materials and aerodynamic design can do considerably better than older designs; however they have not yet achieved widespread use.

Water power was the only source of mechanical power for manufacturing in New England, during the colonial period, and was still significant in mid century. In the early period the technology was the simple water wheel. Hydraulic turbines (c. 1840) constituted a major breakthrough inefficiency. It is difficult to estimate the efficiency of those crude early water wheels; 20% seems a reasonable guess. The water power driving the wheels used in 1800, therefore, would have been of the order of 5 trillion BTU. After the invention of hydraulic turbines efficiencies increased considerably. By 1850 the conversion efficiency had nearly doubled to 39% [Dewhurst 1955]. A modern hydraulic turbine can capture over 90% of the potential energy in the falling water. Water power suddenly became very important after 1890, as falling water — beginning with the exploitation of Niagara Falls — became the cheapest source of electricity.

Internal combustion engines are the most important source of mechanical power today. There are three types. The most common is the spark ignition (gasoline) engine, which dominates in automotive applications. Thermodynamic efficiency at constant speed, without parasitic loads, is about 33%. Losses between the driveshaft and the final service output (passenger km) are discussed later. Pressure ignition (diesel) engines are the next most common type. They are used for some automobiles, heavy trucks, buses diesel electric locomotives, small ships, and offroad equipment. They achieve slightly higher efficiencies, about 36%, under ideal conditions. Finally, gas turbines are used mainly for aircraft, but also for some peak load electric power production. Efficiencies are comparable to diesel engines, although large units can do better.

The efficiency of electric power generation in the early 19th century was extremely low, but since the quantity produced was also infinitesimal, a precise estimate is pointless. Generators achieved roughly 50% efficiency in converting mechanical work to electric power by the 1860s, but virtually the only use was for arc lights, initially in lighthouses. Edison's "Jumbo" generator design of 1878 was the real breakthrough, reaching 80% conversion efficiency. Since then, efficiencies for large units have reached and exceeded the 95% level. The mechanical power, in most cases, is provided nowadays by a steam turbine, so that overall efficiencies — from fuel to electricity at the generator — now range up to 48% at the high end. The average, including transmission losses, is currently about 34%.

The primary or "first law" energy conversion efficiencies (see endnote 10), by category, are summarized in *Table A-II* below. As in the case of *Table A-I*, one can estimate early and recent efficiencies reasonably accurately, but some of the intervening years are interpolations. Doubtless these numbers could be improved by serious historical research, but my purpose here is simply to demonstrate that such analysis is feasible.

Service Delivery Efficiency

Services can be subdivided into two categories, intermediate and final. Intermediate services are performed for other sectors. For instance, space heat, illumination, industrial heat and freight transportation are all partly used by other sectors. Manufacturing and "feedstocks" are consumed only by other productive sectors, not by final consumers. It is possible to estimate service efficiencies (as illustrated below) for some of these cases, but not for all. In particular, it is impossible to estimate directly the efficiency with which manufactured products provide final services to consumers. Facing this difficulty can be postponed, however.

Table A-II: Energy Conversion Efficiencies, First Law: (%)

Category	1800	1850	1900(1)	1940	1960(2)	1979(3)
Space heat	8	8	20	40	60	70
A/C & refrigeration	na	na	na	4	5	6
Cooking & washing	na	na	20	40	60	70
Lighting(a)	8	10	18	28	32	34
Farming & construction	10	10	10	20	30	32
Transport drive(b)	10	8	5	25	30	32
Machine drive(c)	20	1.9	10	20	25	28
Industrial(e)	5	10	15	20	25	27
Other(inc. feedstock)	na	na	10	18	20	22

(a) assuming delivered exergy for light to be flame before 1900 and electric thereafter.
(b) assuming one third of working animals used for transportation purposes, and that animals were the only source of transport power in 1800 .
(c) not including machines producing electric power
(d) included in the "Industrial" category
(e) equated to the efficiency of pig iron smelting in the 1800 period
(1) except as discussed in the text, data in this column is estimated by the author
(2) data in this column is largely taken from [Hirst & Moyers 1973]
(3) data in this column is largely taken from [Ayres 1989a]

It is convenient to start by considering straightforward energy services, namely heating, cooling and lighting. Here it is important to distinguish between two methods of calculating efficiency, which is especially important when discussing heat and it's uses. The crude thermal efficiency of space heating by fuel combustion, discussed in the previous section, was calculated as the ratio of heat delivered to the room to the total heat generated by the fire. It did not reflect the fact that the heat was generated at a high temperature that *could have* accomplished a lot of useful work (for instance, by generating electricity) which could, in turn, have "pumped" lower temperature heat from some reservoir into the space — or better still — into the immediate vicinity of the persons occupying the room. An electric blanket offers as good or better foot warming service to sleepers in a bed than a warm bedroom, not to say a warm house.[23]

Anybody with a good imagination can see ways of reducing energy requirements for space heating to nearly zero, given unlimited capital. However, it is helpful to look at the question more narrowly, in terms of the ratio between the minimum amount of energy (actually exergy) required to achieve a given function — say, maintaining the temperature of a house at 70 degrees F — *vis a vis* the actual exergy consumed for this purpose at a given point in time. The ratio just defined has been called "second law efficiency". In general, second law efficiency is much lower than first law efficiency. The space heating case, in particular, has been examined in some detail by engineering analysts, for a variety of different configurations. An overall estimate of 6% for the second law efficiency for space heating in the U.S. as of 1970 [Carnahan *et al* 1975, Table 2.8]. Recall that the "first law" energy efficiency for space heating (as previously noted), was already 60% by 1955. In earlier years the second law efficiency would have been lower in proportion. Thus, if first law efficiency was 8% in 1850, second law (exergy delivery) efficiency would have been around 0.8%.

The foregoing takes into account the delivery of warm air in the room; it does *not* yet take into account true final service delivery efficiency — the efficiency with which the occupant of the room is warmed. In fact, a well insulated house that captures a reasonable amount of the solar energy impinging on it's windows requires little or no heating at all, as has been demonstrated many times by architects. Similarly, a good warm sweater can be a good substitute for space heating. At night, an electric blanket can be more effective than a radiator. Anyone who writes, types or plays the piano has noticed that warm hands are important, but the rest of the body can be much cooler. Why not an infrared heater focussed specifically on the hands? A footwarmer may also be a more efficient substitute than a room heater, for many situations. However, while these considerations imply that the potential for future energy conservation is considerably greater than the efficiency figures tabulated in *Table A-II* imply, they do not affect the utility of the latter as measures of the state of technology over time.

Water heating in the first half of the 19th century was a parasitic batch process; a bucket of water was heated "on the hob" by the heat of the fire in the fireplace. Assuming the service in question was (mainly) for washing clothes and bathing persons, this process was even less efficient than space heating, since the warm water quickly lost much of it's heat to the bucket or the bathtub. When stoves were introduced the situation improved significantly. However, to be conservative, one can apply the same rule as for space heating. The estimated second law efficiency of water heating in the U.S. in 1970 was only 3% [Carnahan *et al* 1975]. This implies an efficiency of 0.3% in 1850 — which is probably generous. NB it should be pointed out that even the 3% figure does not reflect potential savings through the use of cold water detergents that have since become available and which sharply reduce the amount of hot water needed for laundries and dishwashers.

Cooking in the early 19th century was also largely dependent on the fire in the fireplace. Later stoves were introduced specifically for cooking purposes, but at first these were available only to the urban middle class. Not until the end of the century were kitchen stoves more generally available. Subsequent innovations include the substitution of gas for wood, coke or coal, electrification (using resistance heat), and most recently microwaves. Because of heterogeneity and lack of detailed data, the second law efficiency of cooking — defined in terms of heating the food — was not specifically estimated by the AIP Summer Study [Carnahan *et al* 1975], but it would probably be roughly comparable to the efficiency of water heating, for all periods. Again, this would be an upper limit, since there may also be a variety ways to reduce the amount of heat *needed* for cooking. Microwaves are a great step forward in this regard, since they eliminate the need to heat a lot of dead mass (pans and water) in addition to the food itself.[24]

Similar considerations hold for refrigeration and air conditioning. Refrigeration was available only from ice (stored in insulated iceboxes), in the 19th century and well into the present one. Ice was a major export product of New England). Small electric motors and compressors made refrigeration feasible on the domestic scale. The average second law efficiency, as calculated by Carnahan *et al* for 1970 was about 6%. Since then, thanks to pressure by governments and consumer groups, major improvements have occurred and the best performing units on the market are nearly three times as efficient. However, refrigerators last up to 20 years and penetration of the market as a whole is slow.

Again, the major final service provided by refrigeration is preservation and storage, of perishables. (Provision of ice cubes and chilled drinks is a minor aspect). Already, alternative methods of preservation and storage are being introduced — e.g. for milk — that do not require refrigeration. Also, thanks to marketing by manufacturers, people tend to refrigerate things that would be better left at room temperature (such as butter). Thus, it is difficult to estimate the true service efficiency in this case, except that it is surely considerably less than 6%. Air conditioning is comparable to space heating. Insulation is an effective substitute in many situations (hence adobe houses), and ventilation plus evaporative cooling may be quite adequate in a dry climate. Also, it is not necessary to cool all the air in a house to be comfortable. However, it is very difficult to estimate the minimum need in this case.

Lighting is a special case, since the technology has changed radically. In 1800 the primary source of light (apart from open fires) was candles. By 1850 various sorts of oil lamps, and some gas lamps were being used. Arc lights were being introduced in the 1870s. Edison's incandescent light was a big step forward, but of course it did not replace all other forms of illumination for many years. In 1900 oil lamps and gas lamps were still widely used. However, by 1940, lighting had become essentially fully electrified and the tungsten filament incandescent light was standard. Fluorescent lamps have higher lighting efficiency, but they had not yet achieved really wide use. Nordhaus has tabulated lighting efficiencies in terms of lumen/watt (equivalent) delivered at the lamp [Nordhaus 1994, Table 3]. A tallow candle of 1800 or 1850 delivered 0.0757 lumens/watt; a sperm oil lamp c. 1850 delivered 0.135 lumens/watt. A Welsbach gas mantle of c. 1900 delivered 0.6 lumens/watt (town gas); an incandescent electric lamp of the same period produced 3.71 lumens/watt (electricity). By 1940 that figure had increased to 11.9. By 1980 it had increased only slightly further to 12 lumens/watt or 6%of the theoretical maximum of 200 lumens/watt. It is interesting to note that modern compact fluorescent lamps produce 68 lumens/watt are nearly 5 times more efficient, or about 34%.

It is necessary to adjust all these figures to allow for inefficiencies (losses) in refining tallow or sperm oil, producing town gas, and generating electric power. Very roughly, animal oil refinery efficiencies were probably of the order of 80% (perhaps more, since high temperatures were not needed); town gas efficiency was probably around 50%. Electric power generating efficiency was discussed in the last section. The overall efficiency of lighting in 1800 was, therefore, about .03%; by 1850 this had risen to perhaps .05%. For 1900 it is difficult to estimate, given a heterogeneous mix of candles, kerosine lamps, gaslight and electric light. Assuming the gas mantle to have been average, the efficiency would have been 0.15%. Electric lighting at the time would have been around 0.3% efficient. By 1940 electric light was universal and the efficiency had risen to about 1.9%, taking into account the inefficiency of electric power generation and transmission.

As in the previous cases, light delivered at a lamp is not actually the final service. The latter would be light delivered to the object being viewed. Thus, a small light source, with a parabolic reflector can be more effective than a much brighter light that is unfocussed. However, I see no need to attempt to include such considerations in the technical efficiency measure at this stage.

Transportation is a well documented category of service where the distinction between input and output is relatively easy to comprehend. The input, as noted previously, is power delivered to the driveshaft (or to the wheels). The output can be characterized crudely as passenger km or freight MT km. Obviously these measures do not describe the service fully; for passengers, and perishable goods, speed is an important attribute of the service. Comfort, convenience, prestige and so fort are also relevant. But, to simplify, I consider only the crude measures. The equivalent first law efficiency of transport has been equated (roughly) to the maximum theoretical thermal efficiency of the prime movers involved, viz, gasoline or diesel engines, diesel electric locomotives or gas turbines. This is the conventional approach to estimating transport energy efficiency at the national level [e.g. Bridges 1973].

But this simplistic measure clearly does not reflect losses in service delivery, of which there are many. Thus, a gasoline engine operating under ideal conditions at constant speed with no parasitic loads can convert 33% of the chemical energy in the fuel to mechanical energy. (A diesel engine can do about 36%). However, a few years ago the situation looked more or less as follows [Carnahan *et al* 1975]: operating under realistic traffic conditions, with acceleration, deceleration, gear changing and idling, the maximum efficiency drops by a third, to 22%. Frictional losses in the drive train — mainly the clutch, transmission and universal gears — cost another quarter (to 17%). Parasitic loads, such as water pump, oil pump, power brakes, electrical system and air conditioning, as well as the emissions control system, bring the average down to 11% or so, not counting automatic transmission which costs another 2% to 3%. (Most American cars are automatics, today.) Also, there are losses at the petroleum refinery (about 9% of input) which account for another percent. So the second-law efficiency of the typical American automobile is of the order of 7%.

To be sure, manufacturers have reduced fuel consumption significantly in recent years. But they have not done so by increasing the thermodynamic efficiency of the engine. In fact, since the abolition of lead as an antiknock additive, engine compression ratios have actually dropped significantly to accommodate lower octane fuels. Improved fuel economy has been achieved simply by reducing the power required to run the vehicle by (1) cutting weight, (2) reducing tire friction, and (3) reducing air friction. Internal losses have also been reduced to some extent by adding an extra gear and utilizing more electronics to achieve finer engine controls.

But that applies only to the vehicle. The biggest single loss in the transportation system arises from the fact that the engine must move not only the passenger or payload, but the entire vehicle, including itself. Most of the mass moved is deadweight. This was also true for pre-automotive transport, although the weight of a cart or carriage was normally a smaller multiple of the payload weight; on the other hand, due to primitive bearings and poor roads, frictional losses were far higher. In the case of an automobile, with an average weight of 1000 kg, and a load factor of 1.6 or so, the weight of the passengers and their belongings, on average, is less than 200 kg. So 1000 kg of vehicle (plus some fuel) is moved for the sake of moving 200 kg or so of payload. This amounts to a *payload efficiency* of the order of one part in five or 20%. (Incidentally, this has increased significantly from 1970, thanks to lighter cars). Combining the thermal efficiency and the payload efficiency brings the overall efficiency of service delivery down to around 1.5% or so. The real advantage of public transportation is that payload efficiencies can be higher. Airlines, for instance, routinely operate at load factors in the 70% range; on the other hand they are forced to carry very large parasitic loads of fuel. As a rule of thumb, the payload of an airliner in service is about equal to the weight of the fuel (fully loaded) and the unloaded weight of the aircraft itself. The overall service efficiency of air passenger transportation is therefore around 5.5% [Ayres 1989a].

Freight transportation deserves special comment. Long distance diesel tractor trailers typically operate near full load capacity by treating trailers as portable containers, leaving empty trailers at each destination for reloading and switching to fully loaded trailers for the next leg of the journey. On the road they also accelerate and decelerate much more gradually, operating more of the time at optimum speed and requiring far less power per unit weight of load than passenger vehicles. Finally, they waste comparatively less energy on operating parasitic equipment than passenger cars. The thermal efficiency of such a vehicle can be as high as 20% or even more, and it's average payload efficiency can also be better than 50%, for an overall efficiency in excess of 10%. Railways are significantly better still, in these terms, but count for a relatively small fraction of overall transportation energy. Diesel electric unit trains may achieve combined thermal and payload efficiencies as high as 25%. Small trucks and vans, on the other hand, are often used as private vehicles and, being bigger and heavier, they are even less efficient than private automobiles.

Averaging the service efficiency of passenger and freight transportation together comes to around 6%, for the present mix, give or take one or two percent. Transportation efficiency in 1900 was considerably higher for passengers, but lower for freight. Long distance freight transport was mostly by rail or ship, while urban passenger transport was by rail or streetcar. By 1940 automobiles and trucks were common, but not nearly as dominant as they have since become. Thus, combined transport efficiency probably peaked in the late 19th century.

Table A-III below presents the final (combined) service efficiency estimates. The categories for agriculture, construction, machine drive, industry and "other" do not deliver final services to consumers, and are therefore left out of the table.

Table A-III: Service Delivery Efficiencies, Combined: (%)

Category	1800	1850	1900(1)	1940	1960(2)	1979(3)
Space heat	0.8	0.8	3	5	6	7
A/C & refrigeration	na	na	na	3	5	6
Cooking & washing	na	na	3.00	3	3	5
Lighting	0.03	0.05	0.15	1.90	1.95	2.00
Transport(b)	2	4	8	7	6	6

(b) assuming one third of working animals used for transportation purposes
(c) not including machines producing electric power
(d) included in category "Industry"
(1) except as discussed in the text, data in this column is estimated by the author
(2) data in this column is largely taken from [Hirst & Moyers 1973]
(3) data in this column is largely taken from [Ayres 1989a]

Manufacturing is much more difficult to analyze. A thorough analysis of exergy efficiency in the manufacturing sector would be a major study in itself. (In fact, such studies have been done for the process industries [e.g. Gyftopoulos *et al* 1974; Hall *et al* 1975]). There are three generic components of the manufacturing process: physical separation, chemical transformation (reduction, purification, synthesis) and physical transformation (shaping and forming). Physical separation tends to be quite inefficient in second law terms but the total amount of energy expended on this stage is not great. Metallurgical and chemical transformations range from 20% to 30% conversion efficiency, in second law terms. These efficiencies have been calculated for the most energy intensive sectors (e.g. steel, aluminum, copper, cement, paper, chlorine, petrochemicals). There have been improvements of a few percentage points in the last twenty years, but these are all mature capital intensive sectors where technical change involves large scale investment.

Many complex chemical processes are much less efficient, but again they do not consume much energy *in toto*. Rolling, stamping, extrusion, drawing and molding also probably average 20%–30% efficiency. Machining and grinding of metals, however, is an exception; efficiency may be as low as 1%. Still, an estimate of 25% "first law" efficiency for the manufacturing sector is probably not far wrong [Ayres 1989]. As regards "second law" efficiency, taking into account all possible ways of producing the same final services generated by products, I cannot estimate it directly. Nor can I estimate the efficiency with which intermediate sectors like agriculture and construction deliver their services to other sectors. I do not attempt it. Instead, I make the rather heroic assumption that the ratio between first and second law efficiencies for these categories is the same as for direct energy services, namely about a factor of ten. In short, I estimate final service delivery for industry, construction and agriculture as one tenth of the corresponding first law thermodynamic efficiencies as estimated in *Table A-II.* This assumption is defensible on two grounds. First, the total amount of energy involved is considerably less than that consumed in direct services. And second, it is consistent with the notion that energy efficiency is a reasonable proxy for technical efficiency in general.

Actually the true ratio or first and second law efficiencies is probably much larger. It is increasingly obvious that many "final services" — certainly education, communication and entertainment — really consist of pure information. Information has an infinitesimal energy "content" Tribus & McIrvine 1971]. Certainly, the service output of information processing systems per unit of energy input has been rising spectacularly for several decades. The limits are probably still far away. The path-breaking science-fiction book *Neuromancer* by William Gibson illustrates a world in which humans utilize special microchips (embedded in their skulls) that by-pass the normal sensory channels and permit them to "jack in" directly to "cyberspace". While this notion is somewhat fanciful, it is not scientifically altogether out of bounds. This being so, my factor of ten is probably quite conservative.

Multiplying the efficiency estimates of *Tables A-II and A-III* above with the share data in *Table I,* yields a composite estimate of the technical efficiency for each category of use and for the economy as a whole. Recalling that all of the tables were presented in terms of percentages, the product is given as a decimal fraction in *Table A-IV.*

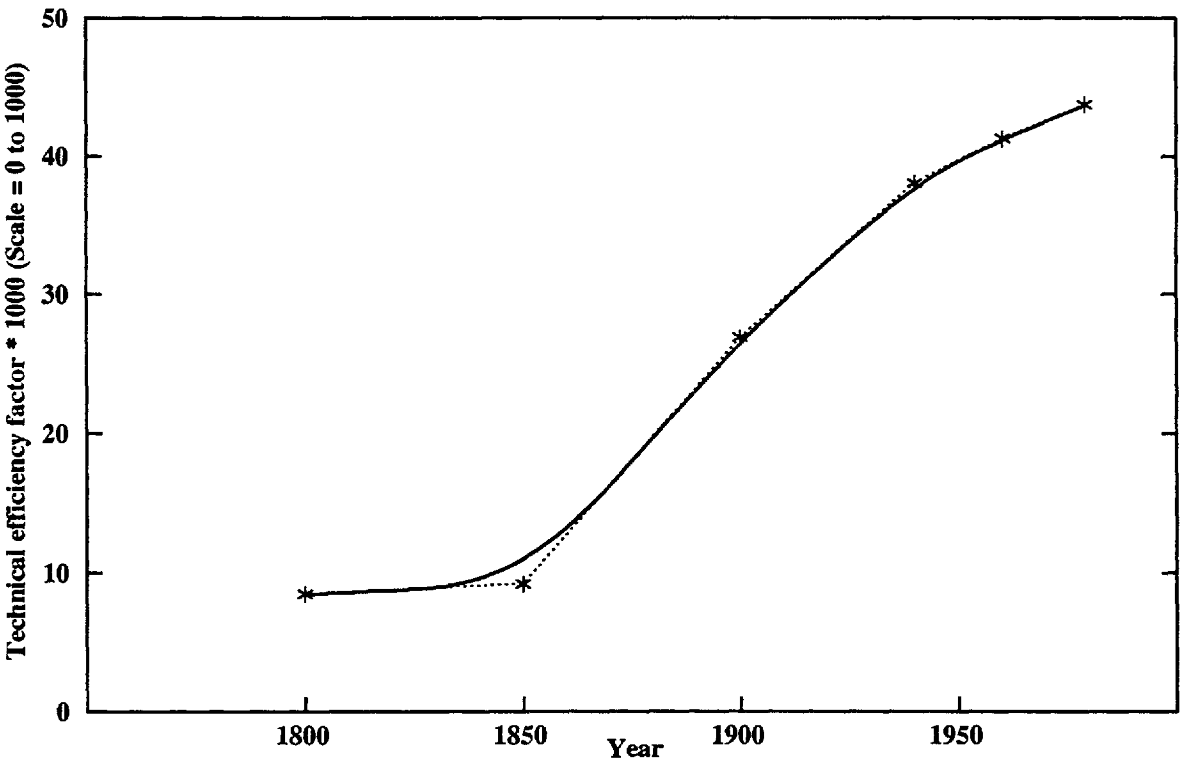


Figure A-1: Technical Efficiency of the Economy

The results are plotted in *Figure A.1.* It is worthwhile calling attention to three points. First, it will be noted that the curve is vaguely S-shaped: it has a distinct resemblance to the so-called "logistic" curve, but it is not symmetric. The inflection point occurs between 1850 and 1900 at a very low level of technical efficiency. Second, even if I have considerably overestimated or underestimated the second-law efficiency of industry and the intermediate sectors, the results would not be qualitatively different. Third, and most important, there is still a great deal of room for technical efficiency improvements.

Table A-IV: Technical Efficiency of the Economy

Category	1800	1850	1900(1)	1940	1960(2)	1979(3)
Space heat(b)	0.00712	0.00680	0.01200	0.01250	0.01110	0.00931
A/C & refrigeration(b)	0	0	0	0.00060	0.00185	0.00360
Cooking & washing(b)	a)	a)	0.00150	0.00150	0.00165	0.00285
Lighting(b)	0.000003	0.00001	0.00003	0.00038	0.00039	0.00080
Farming & construction(c)	0.00050	0.00056	0.00080	0.00120	0.00180	0.00192
Transport drive(b)	0.00060	0.00152	0.00800	0.01400	0.01500	0.01500
Machine drive(c)	0.00020	0.00003	0.00050	0.00120	0.00185	0.00224
Industrial(c)	0.00005	0.00030	0.00375	0.00600	0.00650	0.00540
Other(inc. feedstock)(c)	0	0	0.00030	0.00072	0.00118	0.00264
TOTAL	**0.00847**	**0.00921**	**0.02688**	**0.03810**	**0.04132**	**0.04376**

(a) included in space heat category (row 1) for 1800 and 1850
(b) Calculated by multiplying the corresponding values in Tables I and III
(c) Calculated by multiplying the value in Table I by 1/10 the corresponding value in Table II
(1) except as discussed in the text, data in this column is estimated by the author
(2) data in this column is largely taken from [Hirst & Moyers 1973]
(3) data in this column is largely taken from [Ayres 1989a]

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Endnotes

1. This reasoning goes back to Adam Smith. Smith recognized, however, that some labor is productive and some is not. Work on a farm or in a factory is productive. But the work of a lawyer, a preacher or a soldier is not. In the Marxist system, only the former is considered to have "value" and is counted in the national accounts, which is why services were never developed in communist countries. But, apart from this distinction, the value of labor obviously depends on the skill and training that lie behind it. But, as Joan Robinson notes, it is circular and illegitimate to value labor hours based on wages paid, if the true measure should be the amount of (abstract) labor inputs required to impart the skill [Robinson 1962 p. 44]. Under current conditions, it is questionable that unskilled labor can be regarded as scarce, although the supply is theoretically limited.

2. Capital was defined by Jevons as "the aggregate of those commodities which are required to sustain laborers" [Jevons 1871 p. 226].

3. Yet, this is not a new discovery. For instance, Nassau Senior wrote in his *An Outline of the Science of Political Economy*, published in 1836 "If the labor and skill now employed throughout England on the manufacture of cotton were doubled, but the quantity of raw materials remained the same, the quantity of manufactured produce could not be sensibly increased" (p.82) . (I am indebted to Paul Christensen for this quote). A more recent, if somewhat obscure, statement of the law of conservation of mass in economics is attributable to Tjalling Koopmans, who insisted on — in the context of his discussion of activity analysis — "the impossibility of the land of Cockaigne" [Koopmans 1951]. Unfortunately, Koopmans did not point out the implications for neoclassical production functions.

4. For early work see [Kuznets 1930, 1963]. The history energy consumption per unit of GNP for the U.S. was first calculated in detail by [Schurr & Netschert 1960], based on Kuznets' estimates of GNP for the years before 1910 and Kuznets-Kendrick's estimates of GNP in 1929 prices, later years also based on *National Income and Products Accounts of the United States 1929–1965* [Kendrick 1960], updated in terms of 1958 prices by the Bureau of Economic Analysis (BEA) for later years. For the more recent work involving the so-called Environmental Kuznets Curve (EKC), see [World Bank 1992; Selden & Song 1994; Beckerman 1995; Grossman & Krüger 1995, 1996; Stern *et al* 1996].

5. It is also incompatible with the generalized CES function. It would require something more like a Leontief-type of production function, or perhaps a translog function.

6. In effect, as energy becomes unavailable, it generates *entropy*. (Entropy is measured in units of energy divided by temperature). Thus the economic process necessarily generates entropy. It can be characterized as a process that converts low entropy resources into high entropy wastes. For an extensive discussion of the economic process from this perspective see [Georgescu-Roegen 1971]. The so-called "entropic" school notes that fossil fuels and metal ores constitute a finite stockpile of "low entropy" resources that is being rapidly exhausted by economic activity.

7. About 300 degrees above absolute zero on the so-called Kelvin scale, or 300 °K.

8. The physical units for exergy are exactly the same as for energy or heat, namely Joules, Calories, BTUs, kilowatt hours or horsepower hours. Energy analysts have made matter worse by introducing other units such as million tons of coal equivalent (MTCE), million tons of oil equivalent (BTOE), and "quads" (for quadrillion BTUs). The confusion of units is a major hazard of energy analysis.

9. However, some economists have recently proposed to scrap this assumption e.g. [Romer 1986].

10. Of course, the Cobb-Douglas function is not the only one that satisfies the above conditions. It is only the simplest. In fact, it is a special case of a more general function that now goes by the name CES, referring to its main feature: a constant elasticity of substitution between aggregate labor and aggregate capital [Arrow *et al* 1961].

11. However, Solow, Minhas, Arrow and Chenery — who first introduced the CES production function — tested it on Solow's time series. They first estimated the elasticity of substitution (0.569) and subsequently obtained a slightly higher rate of Hicks-neutral technical progress, viz. 1.83 % per annum [Arrow *et al* 1961]. Kendrick & Sato, using a slightly different method of regression, estimated the elasticity of substitution to be 0.58 which resulted in a significantly higher rate of neutral technical progress of 2.1% per annum [Kendrick & Sato 1963].

12. This study also tested nine different specifications of the Cobb-Douglas production function, using least squares fits to U.S. data from the years 1929, 1949, 1941 and 1947–1969 to determine whether the "best" specification could be distinguished econometrically. The results were surprising. Using the standard Cobb Douglas model, with factors K, L only, *without* an exogenous technological progress term of the Solow type, the best fit (with an R^2 of 0.99495) required increasing returns to scale: in particular the capital share (exponent) was 0.234 and the labor share (exponent) was 0.852. The sum of these two exponents is 1.086, which is significantly greater than unity.

    Hannon and Joyce then tested a number of specifications involving different combinations of K, L, E and El (electricity), assuming constant returns and an exogenous technological progress term of the form e^{rt}. In six cases, retaining labor as one of the factors, with different combinations of K, E and El, extremely good fits to the data were obtained. In all of these six model specifications the best fit was achieved with constant (or very slightly declining) returns to scale and a significant rate of exogenous technological progress r. For five of the six, involving the apparent rate of technological progress r was between 1.30% and 1.38% per annum. All five achieved fits with r^2 values above 0.9994. In the sixth case (assuming factors L and El only) the indicated value of r was 1.68% per annum and the R^2 was only slightly lower, viz. 0.9988.

    Hannon & Joyce also tested two models with K and E or El, respectively, excluding labor L as a factor of production. In one of these cases (assuming K and E to be the only factors) the indicated value of r was 0.84%. In the other case (K and El), the indicated value of r was nearly zero (–.02%). In both of these cases the sum of the exponents was very slightly less than unity, implying nearly constant returns to scale. But these two cases differed dramatically in one surprising respect. When K and E were selected as factors of production, the best fit ($R^2 = 0.99895$) required a capital exponent (share) of only 0.031, and an energy exponent (share) of 0.976. This implies that growth can be explained very well by energy consumption alone, allowing for a small rate of exogenous technological progress (0.84% per annum).

    The other case is even more fascinating. It seems that economic growth can also be explained very well by capital alone, with an exponent of 0.990, with no exogenous technological progress and only a tiny contribution from electricity ($R^2 = 0.99464$). The authors point out that the standard error of the exponents, in this case, was fairly large. Still, this result is so astonishing that it cries out for deeper explanation. But the Hannon-Joyce results, taken together, do strongly suggest that the "right" model specification is unlikely to be uncovered by econometric analysis of historical data. It is unfortunate that this paper was not published in an economics journal [Hannon & Joyce 1981].

13. The transcendental logarithmic functional forms for econometric models of producer and consumer behavior were first introduced by [Christensen *et al* 1971] and described in greater detail by [Jorgenson *et al* 1973] and [Christensen *et al* 1975]. See also [Jorgenson & Lau 1984]. The chief advantages of the translog form are, first, greater flexibility in describing production patterns, especially in a multi sector economy and second, facilitation of the dual formulation of production theory, in terms of factor prices rather than quantities.

14. They first introduced Bayesian updating procedures for model calibration, rather than simply choosing an elasticity parameter from the literature. They then used a slightly modified version of the well known ETA-MACRO model [Manne & Richels 1992] for backcasting to reproduce historical data over a much longer period (1954–1994) than previous studies.

15. Boulding himself apparently borrowed the notion from von Bertalanffy.

16. John Henry was a legendary railway construction laborer — "a steel driving man" — who was celebrated in a well known folk song of the 19th century.

17. In point of fact, the massive increase in returns to financial capital in recent years, especially in the U.S., is surely related to the decreased ability of the U.S. labor movement to appropriate monopoly rents, even though labor productivity has been growing and capital productivity has not.

18. In earlier work I tried to treat all resources, together with technology, as different but equivalent kinds of physical information [Ayres & Miller 1980; Ayres 1987]. I have since realized that this was going too far; they are not equivalent. In fact, I argue later that capital can indeed be regarded as an accumulation of "useful" information.

However, the equivalence between energy E and material resources M is thoroughly justifiable on theoretical grounds [Ayres *et al* 1997-b].

19. The unit "horsepower" was introduced by James Watt in 1783 and defined as 33,000 foot-lb of work per minute. It was based on estimates of the work done by horses used for pumping water out of flooded mines. A horse working on a farm does not work continuously at that degree of intensity; the accepted approximation for a working horse or mule is an output of 1000 hp-hr/yr [Dewhurst 1955]. The power output of a human laborer working an eight hour day is estimated to be about one tenth hp [Encyclopedia Britannica "Power"].

20. It is important to note that these figures are so-called "first law" efficiencies; i.e. they measure the fraction of total heat produced that is captured for space heating purposes (as opposed to going up the chimney). They do not refer to "second law" efficiency, which is the ratio of energy needed to accomplish the purpose in the most efficient possible way to energy actually consumed. A very careful analysis of this issue carried out in 1975 by a summer study sponsored by the National Science Foundation and the American Institute of Physics [Carnahan *et al* 1975] concluded that home heating based on the use of a furnace, steam boiler and conventional radiators is still very inefficient compared to theoretical possibilities, such as heat pumps. In fact, with careful design, good insulation and solar heating, virtually no external energy source is required at all, even in quite cold climates. This point is exemplified by the Rocky Mountain Institute, located in Old Snowmass, Colorado, at an altitude of 8000 feet (2300 meters), which has no central heating system at all. Admittedly, such efficient "high tech" structures are rare and relatively costly today, but the existence of even one example makes two important points: (1) that current heating systems are very inefficient in terms of theoretical potential and (2) that the potential for substituting capital for energy is nearly unlimited.

21. The food intake required by a 70 kg man doing heavy work for an 8 hour day is approximately 5000 Calories. Assuming his work output to be 0.1 hp, this translates into 0.8 hp-hr per day. It follows that 1 hp-hr work output (equivalent 746 watt-hrs or 2.69 megajoules in energy units) involves a food intake of 6225 Calories, or 26.2 MJ. The ratio of output to input is slightly over 10%. It is reasonable to assume that the same ratio would hold for a horse.

22. I think this is probably too high, but it doesn't matter much.

23. There may be other health problems arising from the use of electric blankets, but if so they are irrelevant to the point being made.

24. At first glance the popularity of frozen convenience foods suggests the opposite — that more heat will be needed. However this appearance is deceptive. In the first place, centrally prepared foods can be cooked much more efficiently than foods prepared in individual kitchens. In the second place, frozen foods are easily thawed by contact with water, and they can be heated very quickly by microwaves even without thawing.