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## ACCOUNTING FOR GROWTH: THE ROLE OF PHYSICAL WORK

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# *ACCOUNTING FOR GROWTH: THE ROLE OF PHYSICAL WORK*


**Abstract**

It is argued that the consumption of exergy (available useful energy) has been, and still is, an important driver of economic growth. This paper tests several related hypothesis for explaining US economic growth since 1900. We show that if raw exergy inputs are included with capital and labor in a production function, the historical growth trajectory cannot be reproduced without an exogenous `technical progress' multiplier (the Solow residual). However, introducing the sum total of all types of physical work (by animals, prime movers and heat transfer systems) as a factor of production, the actual growth path is reproduced with high accuracy from 1900 until the mid 1970s and with fair accuracy since then. The unexplained residual during this recent period amounts to about 12% of total growth during the recent quarter century. We suspect that applications of information technology are mainly responsible.

## Background

In the 1950s, it was discovered that the growth in capital stock could only account for a small fraction (about one eighth) of the historical growth in economic output per worker [Abramovitz 1952, 1954; Fabricant 1954]. Economic growth theory was subsequently formulated in its current production function form by Robert Solow and Trevor Swan [Solow 1956, 1957; Swan 1956]. The theory assumes that production of goods and services (in monetary terms) can be expressed as a function of capital and labor, but the major contribution to growth had to be attributed to something else, namely `technological progress' or just `technical progress'. Absent any fundamental economic theory of technical progress, or any convincing independent measure of it, technical progress has been treated as an unexplained residual. This is another way of saying that it is an exogenous multiplier, either of labor or capital or of the whole production function (usually taken to be Cobb-Douglas or CES in form).

There is a further assumption that is very important to the original version of the theory: incomes allocated to factor shares are assumed to be proportional to their relative productivities, as predicted by the theory of income allocation in a perfectly competitive market economy. It follows that factor productivities – the marginal increase in output resulting from a marginal increase in the factor input – are assumed to be proportional to income share in the national accounts. A consequence of this set of interlocking assumptions is that the only factors of production that are accommodated by the standard Solow theory of growth are the two factors receiving shares of national income in the national accounts, namely capital and labor. In the accounting system all of the national income is allocated either to wages and salaries (i.e. returns to labor) or interest, dividends and rents (i.e. returns to capital). The national accounts do not recognize monetary flows `to' natural resources, and if they did, such flows could only be treated as rents flowing to resource owners.

As it happens, however, the Solow model makes two fundamental predictions that do not correspond to historical experience over the last half century. One prediction is that the rate of growth of an economy will decline as the capital stock grows, due to declining marginal productivity of capital and the need to replace depreciation. The other prediction (known as `convergence') is that poor countries, with smaller capital stocks, will grow faster than rich countries.

The most popular `fix' is to dispense with the notion that capital depreciates. Another way of putting it is to assume that depreciation of physical capital is compensated by another effect, namely increasing returns to advances in knowledge, arising from positive externalities (`spillovers'). This notion, first incorporated in the standard theoretical framework by Romer (1986) has prompted an explosion of so-called `endogenous growth' theories [e.g. Romer 1986, 1987, 1990; Lucas 1988; Grossman & Helpman 1991; Aghion & Howitt 1998]. There is a lot of interest among theorists, at present, in the phenomenon of increasing returns to scale (as exemplified by network systems of all kinds). It is important to emphasize, however, that all of this literature is about models that retain the assumption of growth-in-equilibrium.

Most of the so-called endogenous growth theories are so-called A-K models, where K is generalized capital, defined to include knowledge and skills. The Solow multiplier A in these models is supposed to be a constant, independent of time. Labor no longer appears explicitly as a factor. (The new A-K models are essentially throwbacks to the pre-Solow Harrod-Domar growth models [Harrod 1948; Domar 1957]. It is interesting to note that the argument for choosing capital and labor productivities in the Cobb-Douglas production function (on the basis of shares in the national income accounts) no longer applies to the A-K theories.

The major difficulty with the `new' endogenous growth theories is that there is no independent empirical basis for determining what the generalized capital K should be.

**The role of natural resources.**

The possible contribution of natural resource inputs to growth (or to technical progress), was not considered seriously by economists until the 1970s (mainly in response to the Club of Rome and "Limits to Growth"), and then only as a constraint [Dasgupta & Heal 1974; Solow 1974; Stiglitz 1974]. It follows that, in more recent applications of the standard theory (as articulated primarily by Solow) resource consumption has been treated as a consequence of growth and not as a factor of production. This simplistic assumption is built into virtually all textbooks and most of the large-scale models used for policy guidance by governments.

An important `engine of growth' since the first industrial revolution has been the continuously declining real price of physical resources, especially energy (and power) delivered at a point of use.[2] The increasing availability of energy from fossil fuels, and power from heat engines, has clearly played a fundamental role in growth. Machines powered by fossil energy have gradually displaced animals, wind power, water power and human muscles and thus made human workers vastly more productive than they would otherwise have been.

The term energy as used above, and in most discussions (including the economics literature) is technically incorrect, since energy is conserved and therefore cannot be `used up'. The correct term in this context is *exergy*, which is roughly speaking, `available energy' or `useful energy'.[3] We use this term hereafter.

The generic exergy-power feedback cycle works as follows: cheaper exergy and power (due to discoveries, economies of scale and experience – or learning-by-doing – in exergy conversion) enable tangible goods and intangible services to be produced and delivered at lower cost. This is another way of saying that exergy flows[4] are productive. Lower cost, in competitive markets, translates into lower prices for products and services. Thanks to price elasticity, lower prices encourage higher demand. Since demand for final goods and services necessarily corresponds to the sum of factor payments, most of which go back to labor as wages and salaries, it follows that wages of labor tend to increase as output rises.[5] This, in turn, stimulates the further substitution of fossil exergy and mechanical lower for human (and animal) labor, resulting in further increases in scale, etc. and still lower costs.

Based on both qualitative and quantitative evidence, the existence of the positive feedback cycle sketched above implies that physical resource (exergy) flows have been, and still remain, a major factor of production. Indeed, including a fossil exergy flow proxy in the neoclassical production function seems to account for economic growth quite accurately, at least for limited time periods, without any exogenous time-dependent term [Hannon & Joyce 1981; Kümmel 1982, 1989; Cleveland *et al* 1984; Kümmel *et al* 1985; Kaufmann 1992; Beaudreau 1998; Cleveland *et al* 1998; Kümmel *et al* 2000]. [6]T

It is true that even a high degree of correlation does not necessarily imply causation. In other words, the fact that economic growth tends to be very closely correlated with energy consumption – a fact that is easily demonstrated – does not *a priori* mean that energy consumption is the cause of the growth. Indeed, most economic models assume the opposite: that economic growth is responsible for increasing energy consumption. This automatically guarantees correlation. It is also conceivable that both consumption and growth are simultaneously caused by some third factor. The direction of causality must evidently be determined empirically by other means.[7]

More fundamentally, the question arises: why should capital services be treated as a `factor of production' while the role of energy (exergy) services – not to mention other environmental services – is widely ignored or minimized? The naive answer would seem to be that the two factors should be treated on a par. Yet, among many neoclassical economists, strong doubts remain. It appears that there are two reasons. The first and most important is theoretical: national accounts are set up to reflect payments to labor (wages, salaries) and capital owners (rents, royalties, interest, dividends). In fact, GNP is the sum of all such payments and NNP is the sum of all such payments to individuals.

If labor and capital are the only two factors, neoclassical theory implies that the productivity of a factor of production must be proportional to the share of that factor in the national income. This proposition is quite easy to prove in a hypothetical single sector economy consisting of a large number of producers manufacturing a good using only labor and capital services. (It is also taught in elementary economics texts.) Moreover, the supposed link between factor payments and factor productivities gives the national accounts a fundamental role in production theory. This is intuitively very attractive.

Labor gets the lion's share of payments in the US national accounts, around 70 percent. Capital (defined as interest, dividends, rents and royalties) gets all of the rest. The figures vary slightly from year to year, but they have been relatively stable for the past century or more. Land rents are negligible. Payments for fossil fuels (even in `finished' form, including electric power) altogether amount to only a few percent of the total GDP. It follows, according to the received theory, that energy (exergy) is not a significant factor of production, or that it can be subsumed in capital, and can be safely ignored.

However, there is a major flaw in this argument. Suppose there exists an unpaid factor. We might call the unpaid factor environmental services? Since there are no economic agents (persons or firms) who receive income in exchange for environmental services, there are no payments for such services in the national accounts. Absent such payments, it would seem to follow from the logic of the preceding two paragraphs that environmental services are not scarce or not economically productive. This implication pervades neoclassical economic theory. But it is patently unreasonable.

The importance of environmental services to the production of economic goods and services is very difficult to quantify in monetary terms, but that is a separate issue. Even if such services could be valued very accurately, they still do not appear directly in the national accounts and the hypothetical producers of economic goods would not have to pay for them, as such.[8] There are some payments in the form of government expenditures for environmental protection, and private contributions to environmental organizations, but these payments return (mainly) to labor. Moreover, given the deteriorating state of the environment, it seems clear that the existing level of payments is considerably too low. By the same token, the destruction of unreplaced environmental capital should be reflected as a deduction from total capital stock for much the same reasons as investment in reproducible capital are regarded as additions to capital stock.

Quite apart from the question of under-pricing, there is an apparent inconsistency between very small factor payments directly attributable to physical resources – especially exergy – and very high correlation between exergy inputs and aggregate economic outputs. This can be traced to an oversimplification in the theory of income allocation. In reality, the economy produces final products from a chain of intermediates, not directly from raw materials or, still less, from labor and capital. In the simple single sector model used to `prove' the relationship between factor productivity and factor payments, this crucial fact is commonly neglected.

Correcting for the omission of intermediates by introducing even a two-sector or three-sector production process, the picture changes completely. In effect, downstream value-added stages act as productivity multipliers. This enables a factor receiving a very small share of the national income directly, to contribute a much larger effective share of the value of aggregate production, i.e. *to be much* *more productive* than its share of overall labor and capital would seem to imply if the simple theory of income allocation were applicable [Ayres 2001].

It is now convenient to postulate relationships of the form:

(1a) $Y = f_E g E$

or

(1b) $Y = g U_E \quad or \quad g U_{\mathrm{E}}$

where $Y$ is GDP, measured in dollars, $E$ is a measure of commercial energy (mainly fossil fuels), $B$ is a measure of all `raw' physical resource inputs (technically, exergy), including fuels, minerals and agricultural and forest products. Then $f$ is the ratio of `useful work' $U$ done by the economy as a whole to `raw' exergy input (defined below), and $g$ is the ratio of economic output in value terms to work input. All the variables have implicit subscripts $B$ or $E$, which we neglect hereafter where the choice is obvious. Since work appears in both numerator and denominator, its definition depends on whether we choose $B$ or $E$. (Note that equation (*1 a,b*) is merely a definition of the factors *f, g*. There is no theory or approximation involved).

However we note that the expressions *(1a)* or *(1b)* can be interpreted as a production function in either of two cases. The first possibility is that $E$ is a factor of production and the product $f_E\, g$ can be approximated by some first order homogeneous function of the three factors: labor $L$ , capital $K$ and exergy consumption *E*. The second possibility is that work *U* is a factor of production (instead of *E*) and the function g can be expressed approximately by some first order homogeneous function of *K, L* and *U*. We test these possibilities empirically hereafter.

The traditional variables capital *K*, and labor *L,* as usually defined for purposes of economic analysis, are plotted in *Figure 1a* from 1900 to 1998, and deflated GDP and a traditional Cobb-Douglas production function of *K,L,E* in *figure 1b*. It is important to note that GDP increases faster than any of the three contributory factors. The need for a time-dependent factor representing technical progress (the Solow residual) is evident. (It is plotted in the figure.)

The ratio *E/GDP* is the so-called Kuznets curve. It is often observed that, for many industrialized countries, the *E/GDP* (or *E/Y*) ratio appears to have a characteristic inverted `U-shape', at least if *E* is restricted to commercial fuels. (Not to be confused with our variable U). However, when the exergy embodied in firewood is included the supposedly characteristic inverted U-shape is much less pronounced. When non-fuel and mineral resources, especially agricultural phytomass are included, fuel exergy *E* is replaced by total exergy *B*, and the inverted U form is no longer evident. *Figure 2* shows the various exergy inputs, plotted from 1900 to 1998.

*Figure 3* displays three versions of the Kuznets curve. The top curve is the classical version, namely the ratio of commercial (mostly fossil fuel) exergy to GDP. The middle curve is the ratio of all fuels, including firewood, to GDP. The peak is much less pronounced. The third and lowest curve is the ratio of total exergy inputs, including non-fuel exergy, especially agricultural phytomass, to

GDP. The inverted U in the top curve apparently reflects the substitution of commercial fuels for non-commercial fuels (wood) during early stages of industrialization.

**The calculation of physical work.**

As noted earlier, the technical definition of exergy is the maximum work that a system can do as it approaches thermodynamic equilibrium (reversibly) with its surroundings. It is also measured in energy units, and exergy values are very nearly the same as enthalpy (heat values) for ordinary fuels. So, effectively, it is what most people mean when they speak of `energy', except that exergy is also definable for non-fuel materials. We have done the appropriate calculations in other publications.)

However, technically, exergy is also equal to maximum potential work. For non-engineers, mechanical work can be exemplified in a variety of ways, such as lifting a weight against gravity or compressing a fluid. The term horsepower was introduced in the context of horses pumping water from flooded 18th century British mines. A more general definition of work is movement against a potential gradient (or resistance) of some sort. A heat engine is a mechanical device to perform work from heat (though not all work is performed by engines.)

With this in mind, we can subdivide work into three broad categories, namely work done by animal (or human) muscles[9], work done by heat engines (i.e. *mechanical* work) and work done in other ways (e.g. thermal or chemical work). Mechanical work can be further subdivided into work done to generate electric power and work done to provide motive power (e.g. to drive motor vehicles.) The power sources are so-called *`prime movers'*, including all kinds of internal and external combustion engines, from steam turbines to jet engines. So called `renewables`, including hydraulic, nuclear, wind and solar power sources for electric power generation are conventionally included. However electric motors are *not* prime movers, because electricity is generated by some other prime mover, usually a steam or gas turbine.

Chemical work is exemplified by the reduction of metal ores to obtain the pure metal, or indeed any endothermic chemical process. Thermal work is exemplified by the transfer of heat from its point of origin (e.g. a furnace) to its point of use, via a heat exchanger. Electricity can be thought of as `pure' work, since it can be reconverted back into mechanical work or thermal work with almost no loss.

To measure the work done *U*, by the economy in practice, it is helpful to classify fuels by use. The first category is fuel used by prime movers to do mechanical work. This consists of fuel used by electric power generation equipment and fuel used by mobile power sources such as motor vehicles, aircraft and so on. As regards mobile power sources, we define efficiency in terms of the whole vehicle, not just the engine itself. Thus the efficiency of an automobile is the ratio of work done by the wheels on the road to the total potential work (exergy content) of the fuel. Data are available on fuel consumed by electric power generating plants (known as the `heat rate') but the work done is measured directly as kilowatt hours of electric power produced.

The second broad category is fuel used to generate heat *as such*, either for industry (process heat to do chemical work) or space heat and domestic uses such as washing and cooking. Lighting can be thought of as a special case.

So far we have only considered exergy inputs. The inputs for animal work are, of course, feedstuffs. Horses and mules, which accounted for most animal work on US farms and urban transport, have not changed significantly since then. The efficiency with which animals convert feed energy to work is generally reckoned at about 4% (i.e. one unit of work requires 25 units of feed).

The agricultural products that are converted into human food contribute to the economy in the same way as other industrial materials (muscle work by humans is quantitatively negligible). The conversion efficiency for North Americ c.1995 has been estimated as 5.5% (Wirsenius 2000). It is unlikely to be increasing.

Clearly, the efficiency of heat engines, domestic and commercial heating systems and industrial thermal processes has changed significantly over the past 100 years. We have plotted these increasing conversion efficiencies, from 1900 to 1998 in *Figure 4*. (Detailed derivations of these curves can be found in another publication [Ayres et al 2001]). Work by horses and mules (mostly on farms) has also been estimated directly. Other types of work can be estimated from fuel inputs, multiplied by conversion efficiencies, over time, shown in *Figure 5*. Evidently animal work was still significant in 1900 but mechanical and electrical work have since become far more important. Electrification has been perhaps the single most important source of work and (as will be seen later) driver of growth.

Electrical work need not be computed from fuel inputs, since it is measured directly in kilowatt-hours (kwh) generated. The fuel required to generate a kilowatt-hour of electric power has decreased by a factor of nine during the past century. On the other hand, the consumption of electricity in the US has increased over the same period by a factor of more than 1300, as shown in *Figure 6*. (This exemplifies the positive feedback economic `growth engine' discussed earlier.)

Effectively there are two definitions of work to be considered hereafter, namely

2a $U_B = f_B B$

2b $U_E. = f_E E$

The ratios *f* are, effectively, composite conversion efficiencies. The former takes into account animal work and agricultural products, including animal feed. The latter neglects animal work and agricultural production. These two efficiency trends are plotted from 1900 to 1998 in *Figure 7.* Evidently if the trend in *f* is fairly steadily upward throughout a long period (such as a century) it would seem reasonably safe to project this trend curve into the future for some decades. The trends in physical work together with the ratio of physical work to deflated GDP are shown in *Figure 8*. The total quantity of physical work inputs into the economy rise steadily over the entire period and are likely to continue increasing at a similar rate, however the slope of the ratio of work input to GDP changes dramatically around 1970. Prior to this date the GDP output per unit of work input was decreasing. After this date the trend is reversed.

**Eliminating the Solow residual**

There are two important conditions to be satisfied for either version of (1) to be a production function. One of them is the Euler condition for constant returns to scale, which means that *Y* must be a homogeneous first order function of the three independent variables. It follows that the product *fg* must a homogeneous zeroth order function of the same three production factors. The other condition is that the marginal productivities of the three factors be non-negative, at least over a long-term average. (The marginal productivities, logarithmic derivatives of output with respect to each of the factors, need not be constant in time. In fact there is no theoretical reason why marginal productivities should be constant.)

It is already evident from *Figure 1* that the Cobb-Douglas function cannot explain economic growth since 1900. Actually, the constant returns (Euler) condition rules out any function of *K, L, E* or *K, L, B*, since a homogeneous first order function cannot increase faster than all of its arguments.

However, there are other functional forms combining the factors *K, L, E (orB)* that do permit variable marginal productivities and thus provide better fits than Cobb-Douglas, at least over moderate periods. It happens that a suitable functional form (the so-called LINEX function) has been suggested by Kümmel [Kümmel 1982; Kümmel et al 1985], namely

$$Y = A\, E\, \exp\{aL/E - b(E+L)/K\} \qquad (4)$$

where A is a multiplier that should (in principle) be independent of time. It can be verified without difficulty that this function satisfies the Euler condition for constant returns to scale. It can also be shown that the requirement of non-negative marginal productivities can be met.

The three factor productivities are as follows

(5a) $$\delta \ln Y/\delta \ln K = (\delta Y/\delta K)(K/Y) = b(L/K) \geqq 0$$

(5b $$\delta \ln Y/\delta \ln L =(\delta Y/\delta L)(L/Y) = a(L/E) - b(L/K) \geqq 0$$

(5c) $$\delta \ln Y/\delta \ln E =(\delta Y/\delta E)(E/Y) = 1 - a(L/E) - b(E/K) \geqq 0$$

It follows from logarithmic differentiation that the requirement of non-negativity is equivalent to the following three inequalities:

(6a) $b > 0$

(6b) $aK > bE$

(6c) $1 > a(L/E) + b(E/K)$

The variable *E* in the above expressions can, of course be replaced by *B,* without affecting the results. The first condition (6a) is trivial. However the second and third conditions are not automatically satisfied for all possible values of the variables. It is therefore necessary to do the fitting by constrained non-linear optimization. The statistical procedures and quality measures are discussed in the Appendix.

We now consider four cases, plotted together in *Figure 9* .The two lower curves show the best possible LINEX fits to historical GDP growth, starting at 1900, with fuel exergy *E* and total exergy *B* as factors of production. These two fits are obviously unsatisfactory, albeit very slightly better than the Cobb Douglas fits (not shown), meaning that economic growth is not adequately explained by including exergy in the production function (contrary to our starting hypothesis). The unexplained residual remains quite large. An exogenous technical progress term (Solow residual) is needed in either case.

The two upper curves in *Figure 9* show the LINEX fit, where we have replaced $E$ with work $U_E$ and $B$ by $U_B$ respectively as factors of production. For the third case, we consider physical work from commercial energy sources $U_E$ (excluding animal work) as a factor. The last case $U_B$, derived from all exergy inputs $B$ includes animal work and also the corresponding agricultural phytomass (the source of animal feed.) The best fit, by far, is the final one. The unexplained residual has essentially disappeared, prior to 1980 and remains small thereafter. In short, `technical progress' as defined by the Solow residual is almost entirely explained by historical improvements in exergy conversion (to physical work), as summarized in *Figure 4*, at least until recent times. The remaining unexplained residual, amounting to roughly 12% of recent economic growth, is shown in *Figure 10.*

The marginal productivities of the factors can be calculated directly from equations (5), for all four cases; however since the first two cases do not yield good fits, the results are not particularly useful. The three marginal productivities for each of the last two cases are plotted in *Figures 11, 12*, respectively. The marginal productivity trends for capital and work, in both cases show a very slight directional change between 1970 and 1980. The marginal productivity of capital has started to increase whereas the marginal productivity of physical work –

resulting from increases in the efficiency of energy conversion – has declined slightly. This shift roughly coincides with the two so-called oil crises, and may well have been triggered by the spike in energy (exergy) prices that occurred at that time.

The shift can be interpreted as a structural change in the economy, and more precisely, a change in the locus of technological progress from energy conversion efficiency towards systems optimization. For instance, the CAFE standards for automobile fuel economy, introduced in the late 1970s, forced motor vehicle manufacturers to redesign their vehicles so as to double the vehicle miles obtained from a unit of motor fuel in the US between 1970 and 1989. This was achieved mainly by weight reduction and improvements in aerodynamics and tires. Comparable improvements have been achieved in air travel, rail freight and in many manufacturing sectors.

**Towards an endogenous growth model**

In the `standard' model a forecast of GDP requires a forecast of labor $L$, capital stock $K$ and the Solow multiplier – multifactor productivity or technical progress -- $A(t)$. Based on the results described above, the technical progress term can be decomposed into contributions from improved exergy conversion-to-(primary) work efficiency and `other'.

The year 1972 marked a distinct 'turning point' in the economic history of the US. Prior to that year the marginal increase per unit of primary work input was generally falling; a kind of saturation phenomenon. After 1972, the trend was reversed. *Figure 8* expresses this behaviour in terms of primary work / GDP[10]

Evidently growth of GDP since 1972 has slightly outstripped growth of the three input factors, capital, labor and physical work. An additional source of value added is involved. The obvious candidate for this additional value creation is information technology (IT). However, in the spirit of some endogenous growth theories, it would be possible to interpret this additional productivity to some qualitative improvement in either capital or labor.

Clearly primary physical work is still by far the dominant driver of growth. However, this does not mean that human labor or capital are unimportant. The three factors are not really independent of each other. Increasing exergy conversion efficiency requires investments of capital and labor, while the creation of capital is highly dependent on the productivity of physical work.

It is tempting to argue that the observed shift starting in the 1970s reflects the influence of information technology. Certainly large scale systems optimization depends very strongly on large data bases and information processing capability. The airline reservation systems now in use have achieved significant operational economies and productivity gains for airlines by increasing capacity utilization. Manufacturing firms have achieved comparable gains through computerized integration of different functions.

One of the more important implications of the foregoing is that some of the most dramatic and visible technological changes of the past century have not contributed significantly to overall economic growth. An example in point is medical progress. While infant mortality has declined dramatically and life expectancy has increased very significantly since 1900, it its hard to see any direct impact on economic growth, at least up to the 1970s. Greater life expectancy added little to labor productivity. The gain has been primarily in quality of life, not quantity of output. However, it is possible that some of the GDP gains since 1970 can be attributed to increased expenditure on health services.

Changes in telecommunications technology since 1900 may constitute another example. New service industries, like moving pictures, radio and TV have been created, but if the net result is new forms of entertainment, the gains in employment and output may have come largely at the expense of earlier forms of public news and entertainment, such as the print media, live theater, circuses and vaudeville. While the changes have been spectacular, as measured in terms of information transmitted, the productivity gains may not have been especially large, at least until recently. Again, the net impact may have been primarily on quality of life.

In any case, since economic growth for the past century, at least up to 1980, can be explained with considerable accuracy by three factors, $K$, $L$, $U_B$ it is not unreasonable to expect that future growth for some time to come will be explained quite well by these variables, plus a growing contribution from IT. From a long-term sustainability viewpoint, this conclusion carries a powerful implication. If economic growth is to continue without proportional increases in fossil fuel consumption, it is vitally important to exploit new ways of generating value added without doing more work. But it is also essential to develop ways of reducing fossil fuel exergy inputs per unit of physical work output. In other words, energy (exergy) conservation is the main key to long term environmental sustainability.

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**Figure 1a. Traditional Factors of Production K, L, E, USA 1900-1998**

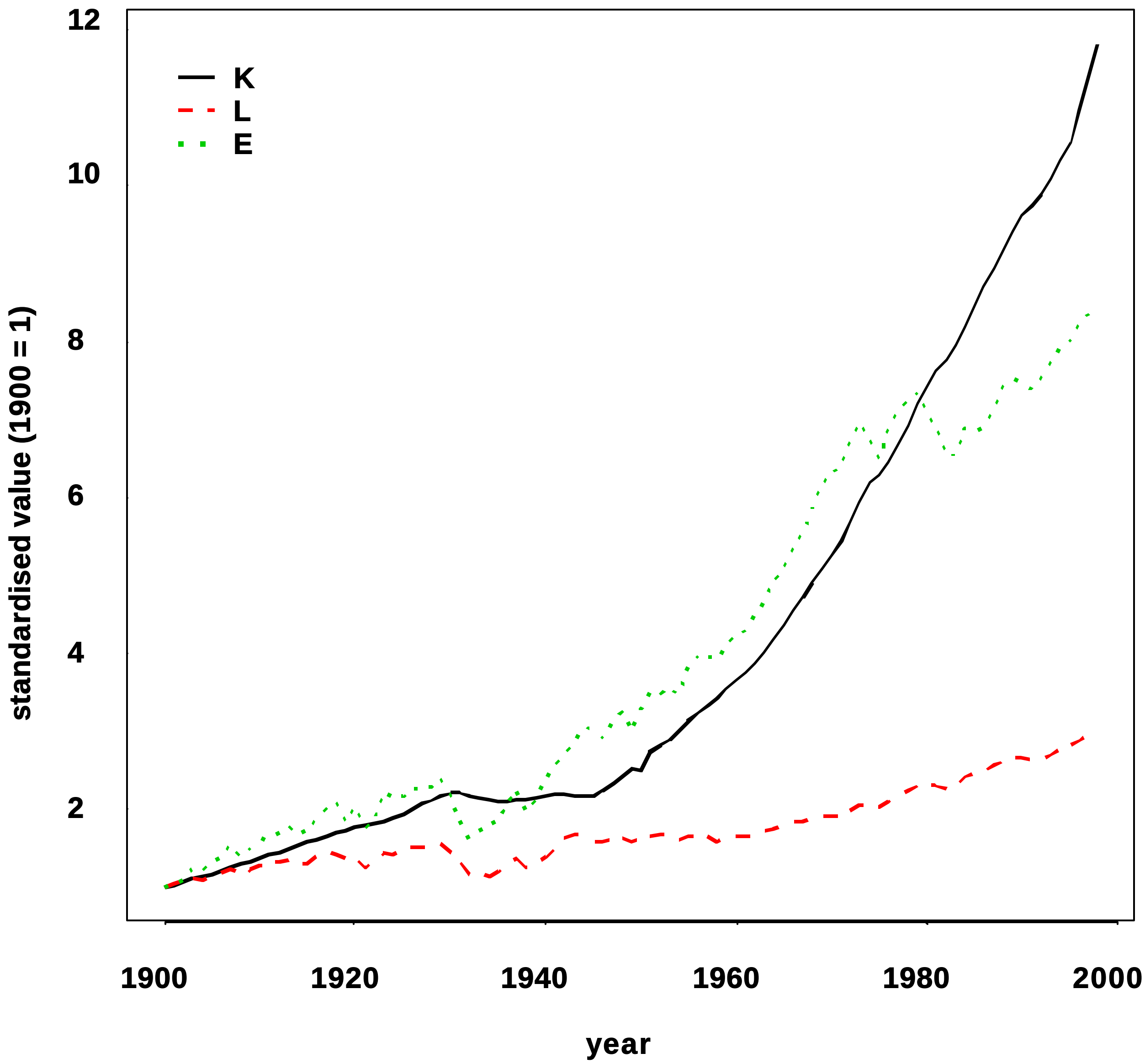
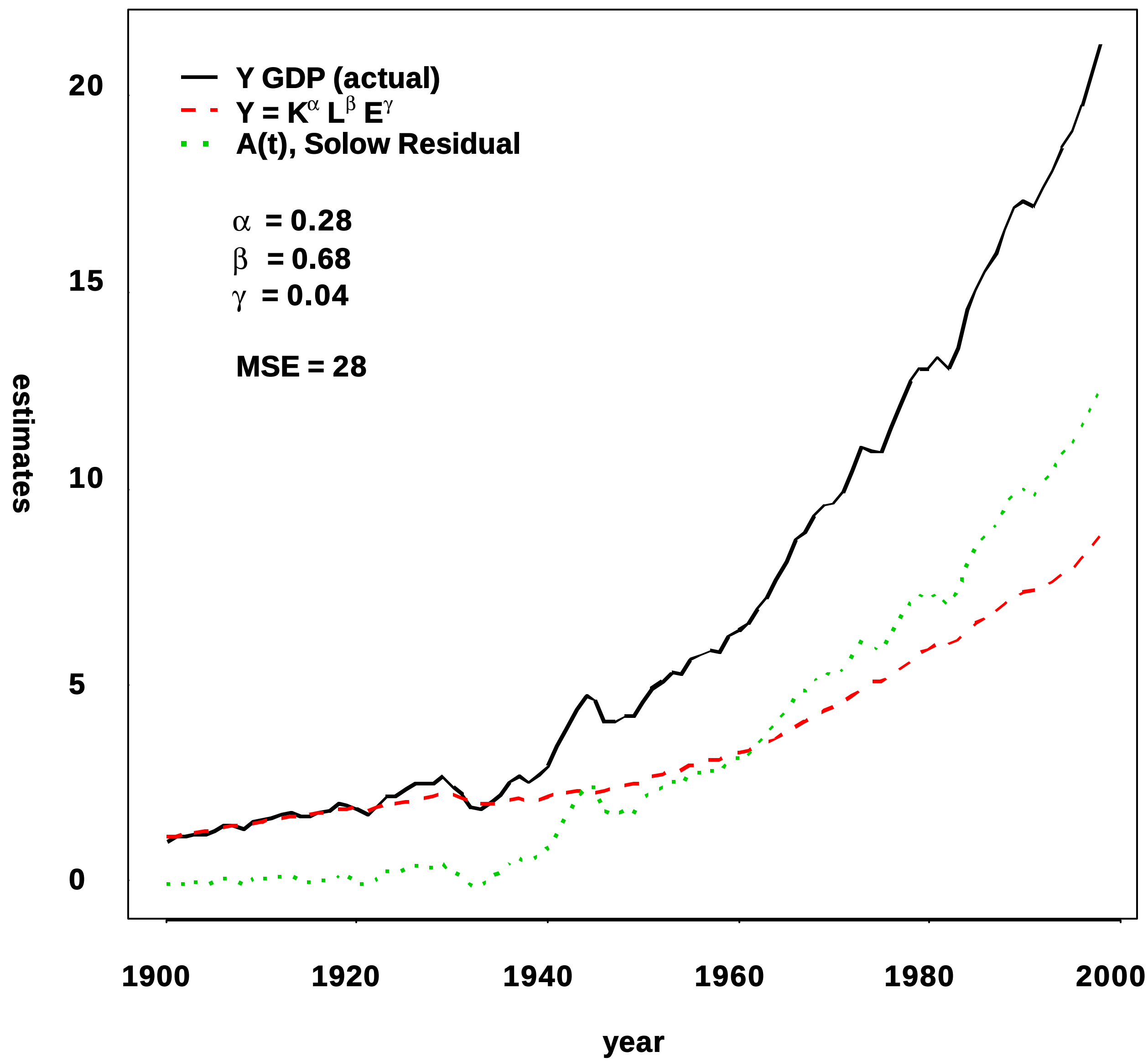


**Figure 1b. Cobb Douglas Production Function and Solow Residual, USA 1900-1998**




Base Year 1900 = 1992 $ 354 billion

**Figure 2. Exergy inputs, USA 1900-1998**

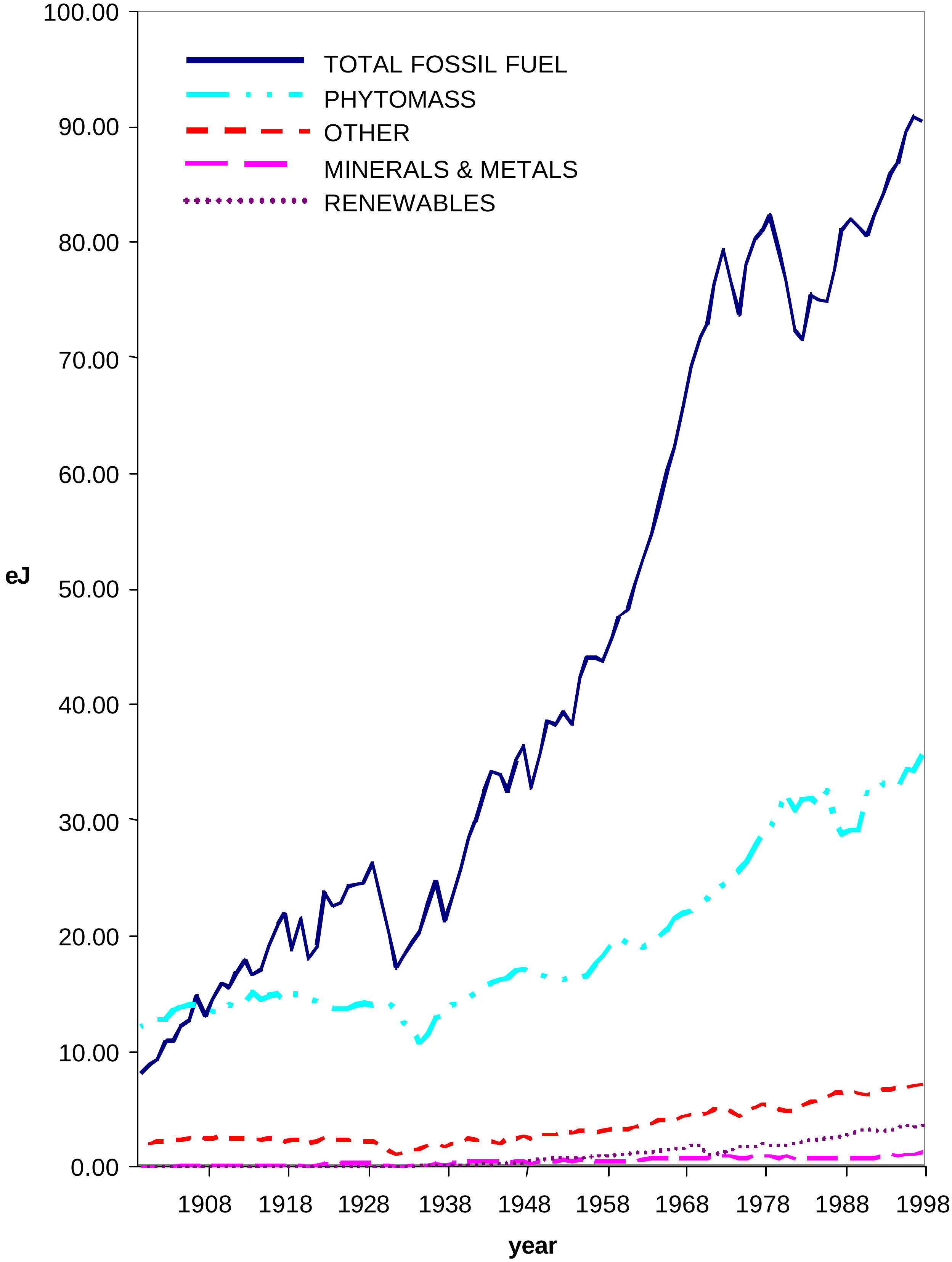


**Figure 3. The ratio of Exergy Inputs to GDP, USA 1900-1998**

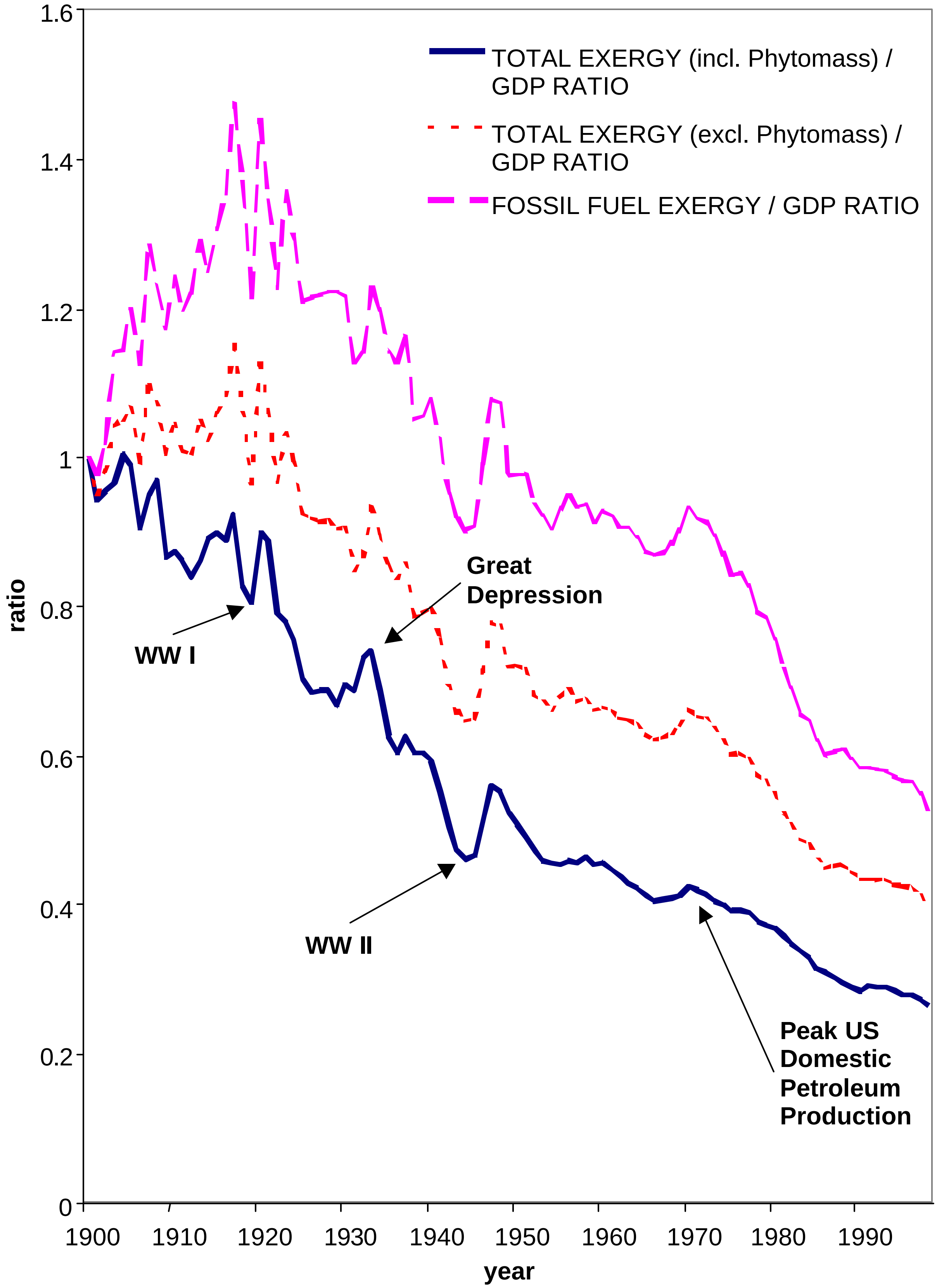


**Figure 4. Energy (exergy) conversion efficiencies, USA 1900-1998**

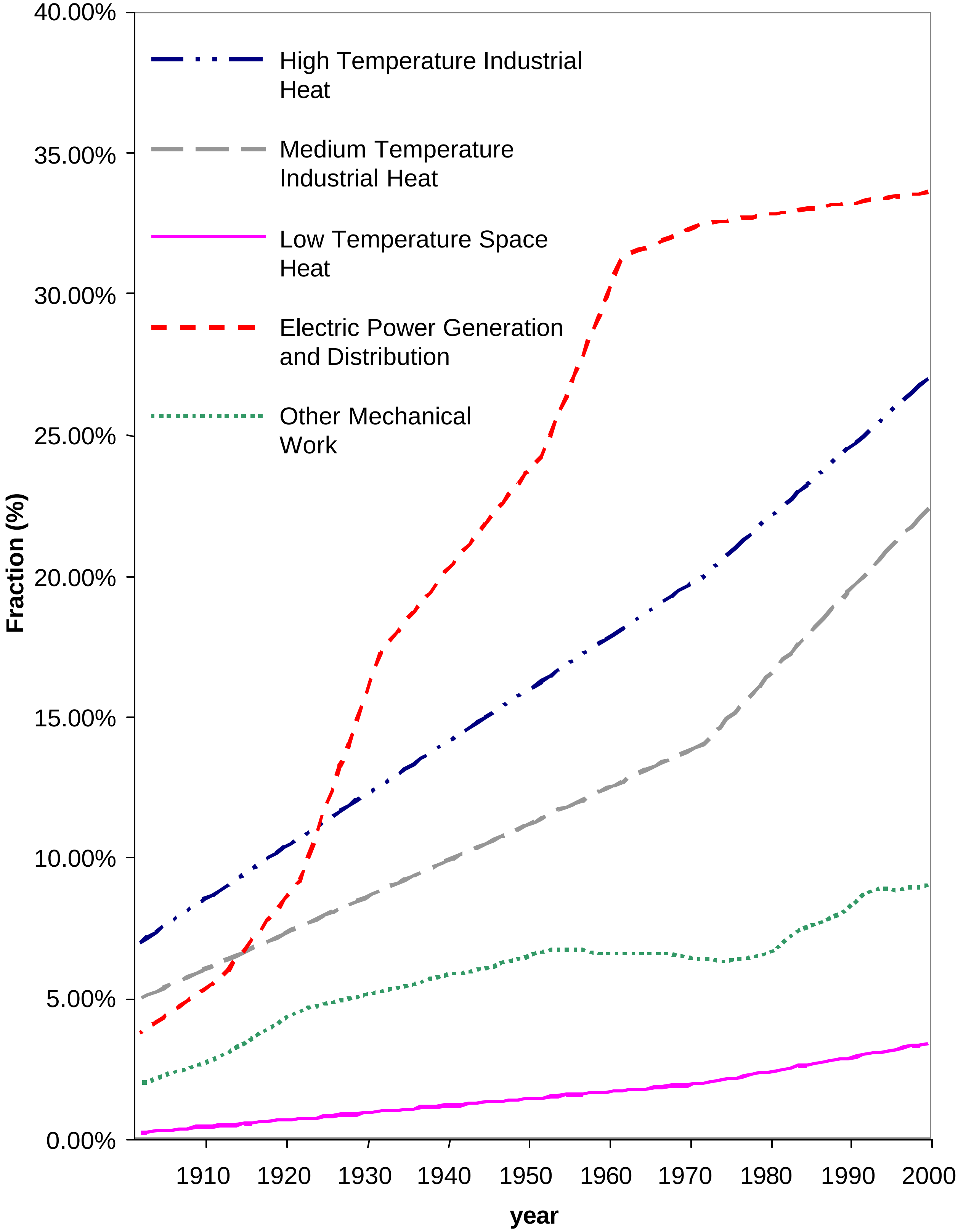


**Figure 5. Allocation of exergy by types of work, USA 1900-1998**

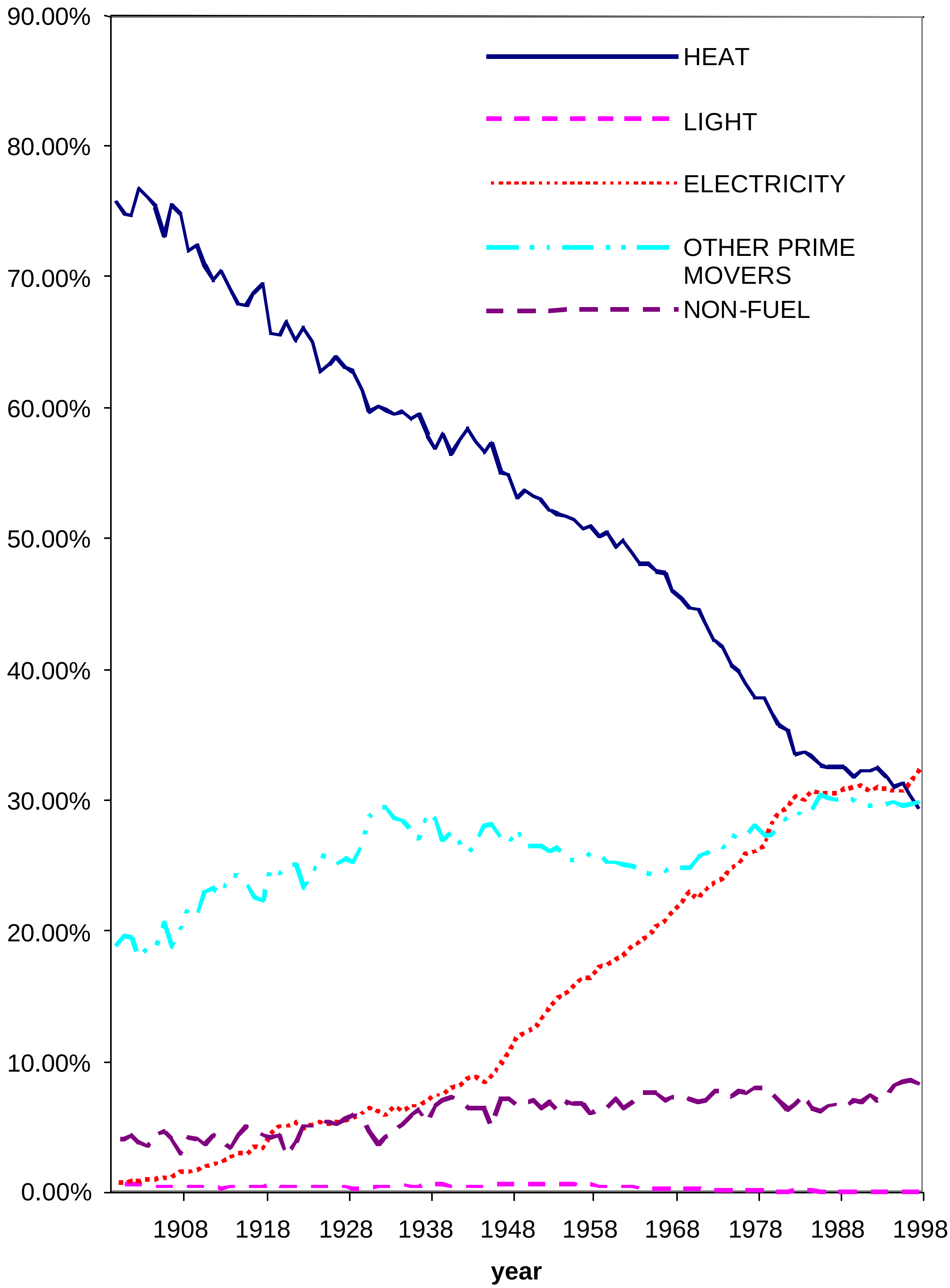


**Figure 6. Electricity production and conversion efficiency**

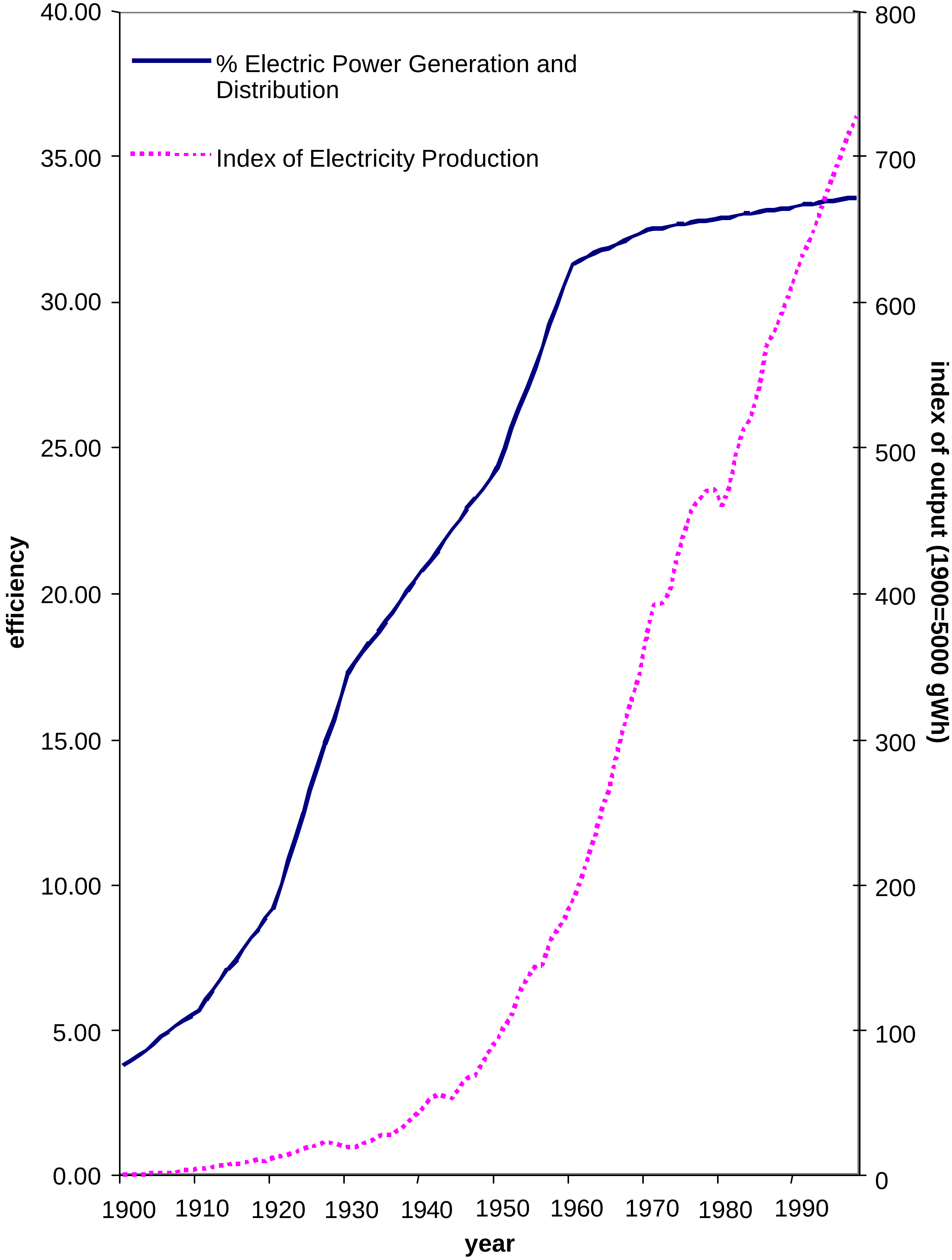


**Figure 7. Exergy conversion efficiency f, for two definitions of work and exergy, US 1900-1998**

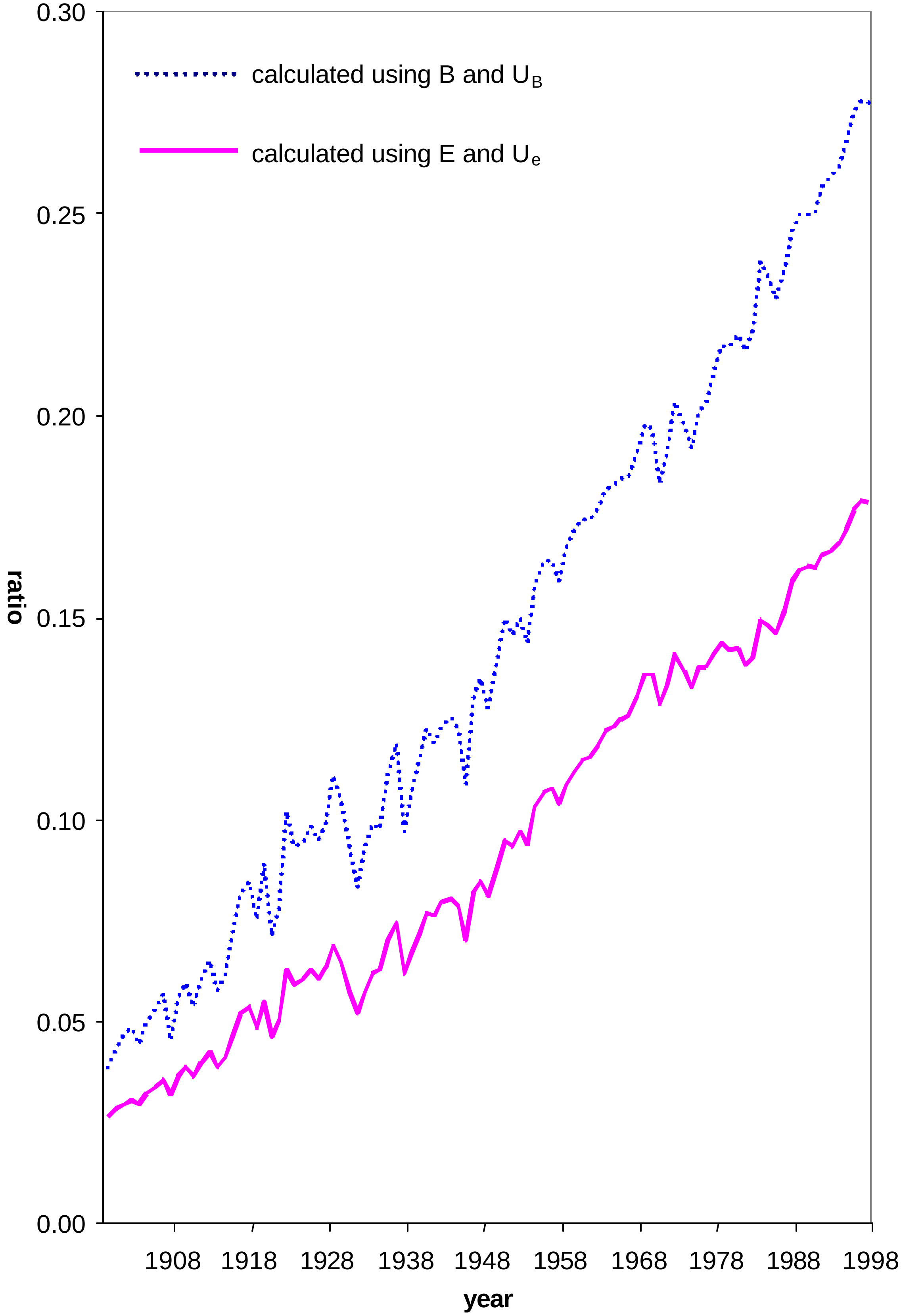


**Figure 8. Primary work and the primary work / GDP ratio, USA 1900-1998**

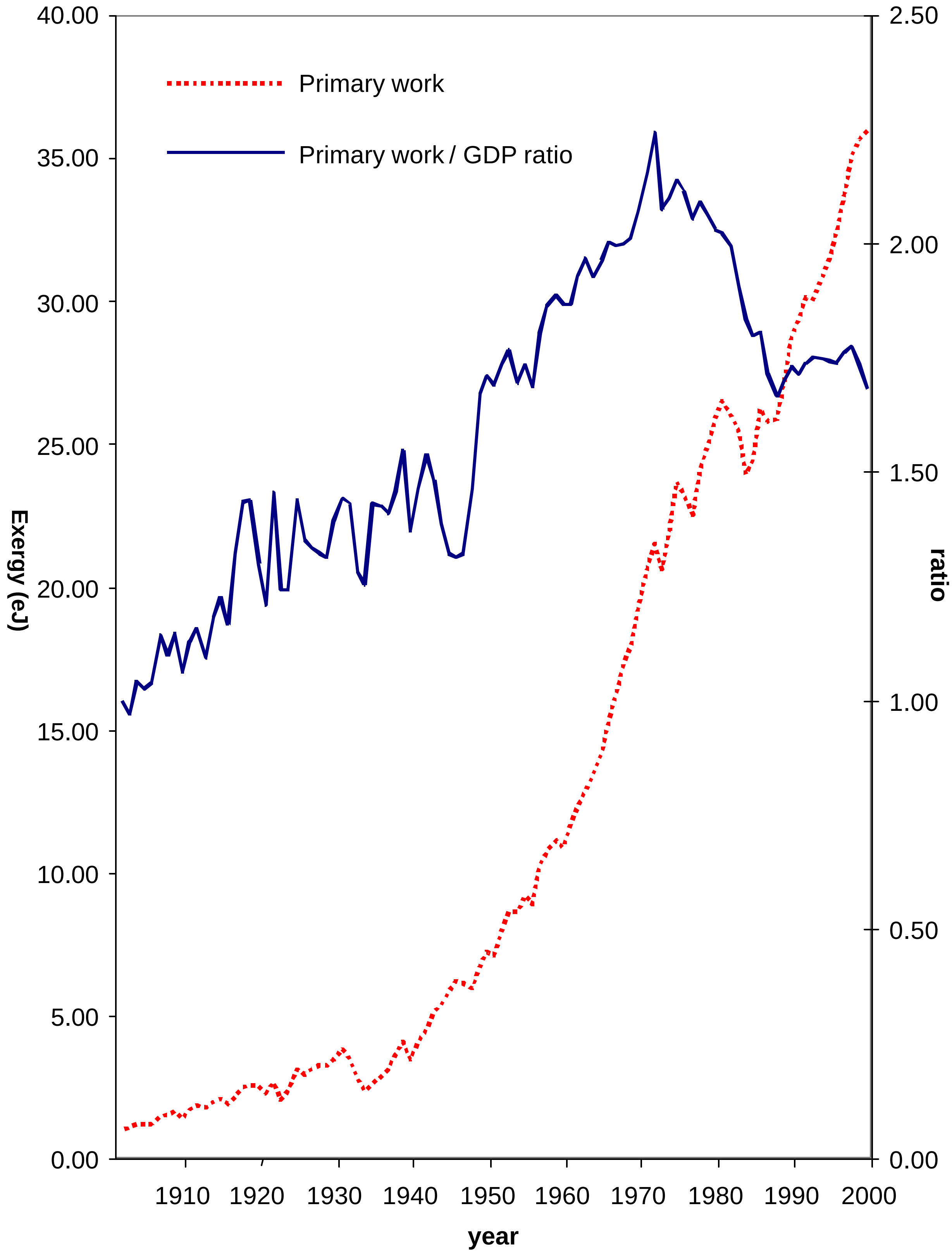


**Figure 9. LINEX production function fits with different 'energy' factor inputs, US 1900-1998.**

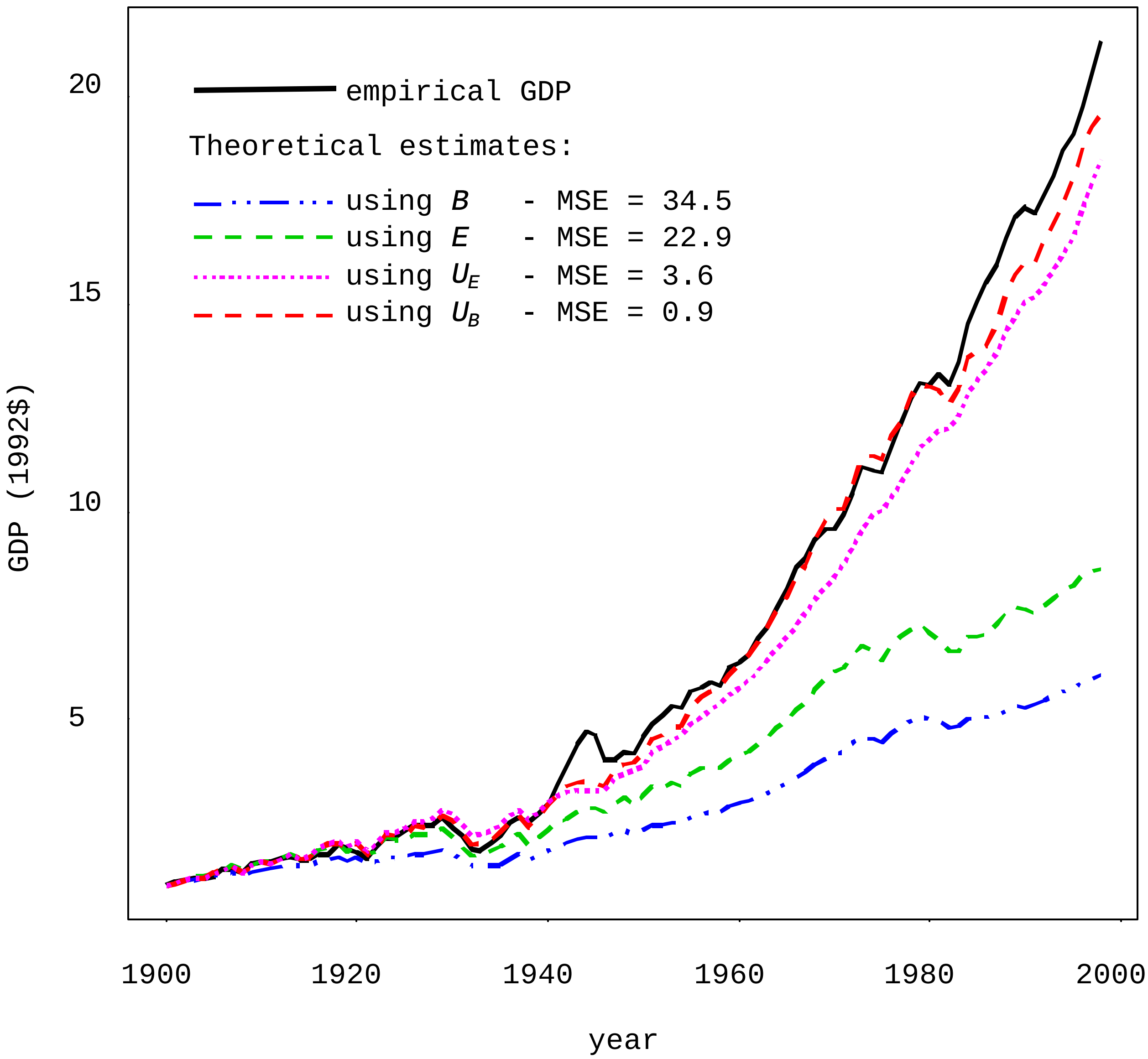


**Figure 10. The percentage of observed growth unexplained by the LINEX fit with 'work' ($U_B$), US 1972-1998.**

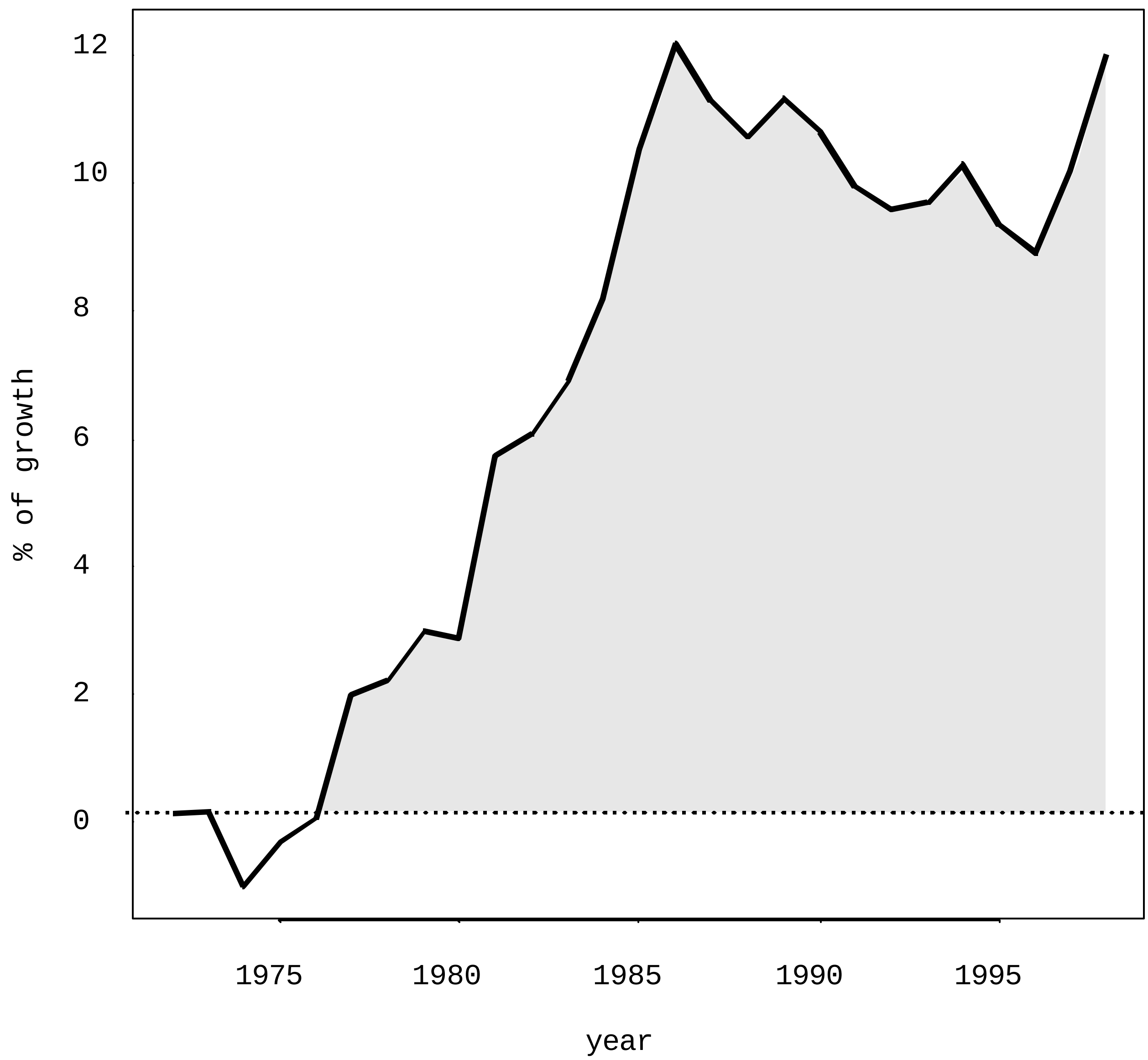


**Figure 11. Marginal productivities (elasticities) of each factor of production using $U_E$ in LINEX, US 1900-1998.**

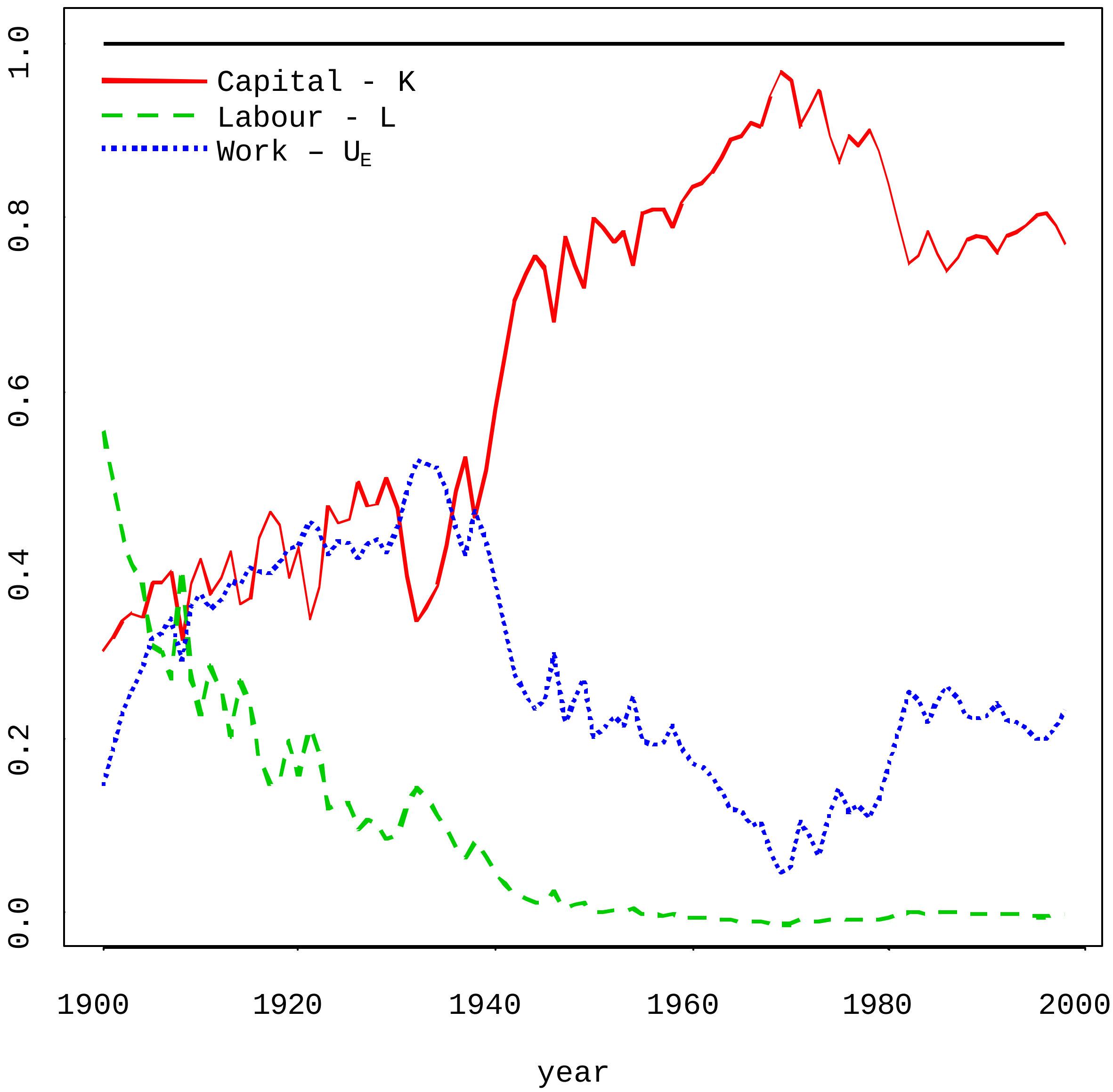
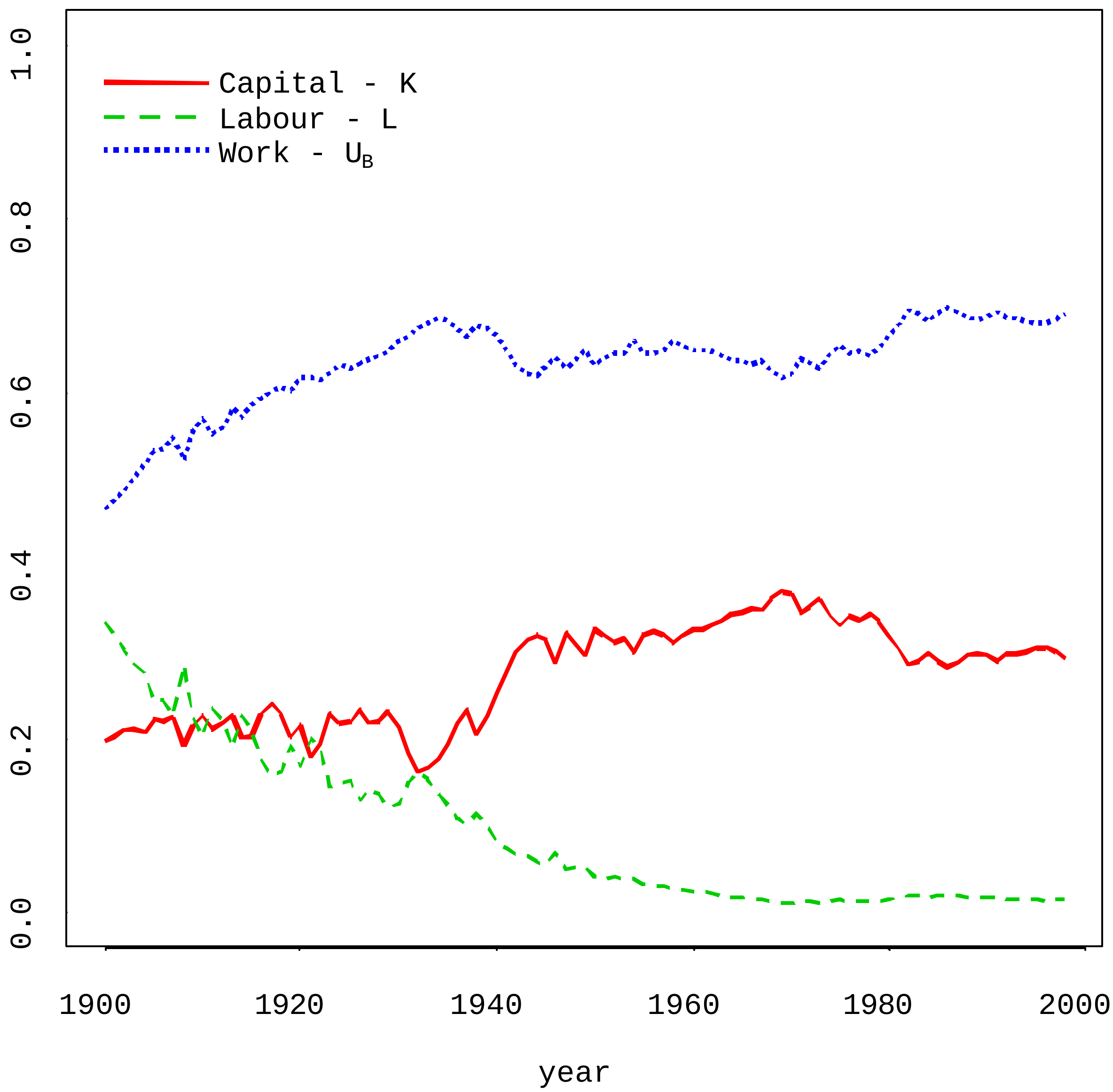


**Figure 12. Marginal productivities (elasticities) of each factor of production using $U_B$ in LINEX, US 1900-1998.**



## Endnotes

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1. Research supported by Institute for Advanced Study, UNUniversity, Tokyo and The European Commission, TERRA project.

2. The tendency of virtually all raw material and fuel costs to decline over time (lumber was the main exception) has been thoroughly documented, especially by economists at Resources For the Future (RFF) [Barnett & Morse 1962; Potter & Christy 1968; Smith 1969].

3. The proper definition of exergy is the maximum work that can be done by a system as it approaches equilibrium with its surroundings. Thus exergy is effectively equivalent to work.

4. Exergy is the correct thermodynamic term for `available energy' or `useful energy', or energy capable of performing mechanical work. The distinction is theoretically important because energy is a conserved quantity (first law of thermodynamics). This means that energy is not `used up' in physical processes, merely transformed from available to less and less available forms. On the other hand, exergy is not conserved: it is used up. The directionality of this transformation is expressed as increasing entropy (second law of thermodynamics).

5. Marx believed (with some justification) that the gains would flow mainly to owners of capital rather than to workers. Political developments have changed the balance of power since Marx's time. However, in either case, returns to energy or physical resources tend to decline as output grows. This can be interpreted as a declining real price.

6. For instance, for the years 1929 through 1969, one specification that gave good results without an exogenous term for technical progress was the choice of K and E as factors of production. In this case the best fit ($R^2 = 0.99895$) implied a capital share of only 0.031 and an energy share of 0.976, (which corresponds to very small increasing returns) [Hannon & Joyce 1981] Another formulation, involving K and electricity, El, yielded very different results, namely ($R^2 = 0.99464$) a capital share of 0.990 with only a tiny share for electricity [ibid]. using factors K, L only — as Solow did in his pathbreaking (Nobel Prizewinning) paper — but not including an exogenous technical progress factor (as he did) the best fit ($R^2 = 0.99495$) was obtained with a capital share of 0.234 and a labor share of 0.852. These shares add up to more than unity (1.086) , which implies significantly increasing returns. Evidently one cannot rely on econometrics to ascertain the "best" formulation of a Cobb-Douglas (or any other) production function.

7. There are statistical approaches to addressing the causality issue. For instance, Granger and others have developed statistical tests that can provide some clues as to which is cause and which is effect [Granger 1969; Sims 1972]. These tests have been applied to the present question (i.e whether energy consumption is a cause or an effect of economic growth) by Stern [Stern 1993; Kaufmann 1995]. In brief, the conclusions depend upon whether energy is measured in terms of heat value of all fuels (in which case the direction of causation is ambiguous) or whether the energy aggregate is adjusted to reflect the quality (or, more accurately, the price or productivity) of each fuel in the mix. In the latter case the econometric evidence seem to confirm the qualitative conclusion that energy (exergy) consumption is a cause of growth. Both results are consistent with the notion of mutual causation.

8. In a recently published economic textbook written by a Harvard Professor, the income allocation theorem is `proved' and illustrated using the example of bakeries producing hypothetical bread from capital and labor, but without flour or fuel. Empty calories, indeed!

9. Human muscular work is insignificant by comparison with other sources of work, and we neglect it. Human labor is a combination of sense-based supervision and coordination and brain work.

10 This is analogous to the so-called Kuznets (inverted U) curve for E / GDP shown in *figure 3* (upper curve).