INSEAD
R & D

Working Papers

# ECONOMIC GROWTH MODELS AND THE ROLE OF PHYSICAL RESOURCES

by

R. U. AYRES*
and
B. WARR**

2002/53/EPS/CMER

This working paper was published in the context of INSEAD's Centre for the Management of Environmental Resources, an R&D partnership sponsored by Ciba-Geigy, Danfoss, Otto Group and Royal Dutch/Shell and Sandoz AG.

* Emeritus Professor of Economics and Political Science at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France.

** Research Associate at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France

# *ECONOMIC GROWTH MODELS AND THE ROLE OF PHYSICAL RESOURCES*

**Robert U Ayres & Benjamin Warr[1]**
**Center for the Management of Environmental Resources**
**INSEAD**
**Fontainebleau, France**
**Email: robert.ayres@insead.edu**

## Background

Conventional economic growth theory assumes that technological progress is exogenous and that resource consumption is a consequence, not a cause, of growth. This assumption is built into most, if not all of the large-scale models used for policy guidance by governments. The reality is more complex. A `growth engine' is a positive feedback loop involving declining costs of inputs and increasing demand for outputs.

The most important `growth engine' of the first industrial revolution was based on coal and steam power, through its impact on rapidly declining fossil fuel and mechanical power costs, and their relationship with scale of production on the one hand and demand for end use products, on the other. The growth impetus due to fossil fuel discoveries and applications, and continued cost reductions, continued through the 19th century and into the 20th with petroleum, internal combustion engines, and — most potent of all — electrification. The advent of cheap electricity in unlimited quantities has triggered the development of a whole range of new products and industries, including electric light, radio and television, moving pictures, and new materials such as aluminum and superalloys without which the aircraft and aerospace sectors could not exist.

In effect, energy consumption within the economy is as much a driver of economic growth as it is a consequence of growth. The argument that energy is an intermediate input, while valid, is not conclusive. Though energy and other natural-resource- based commodities can be regarded as economic intermediates (insofar as they are produced by the application of capital and labor) this is no less true of capital. In fact, the skills and knowledge embodied in the labor force are also products of capital and labor. Of course, it can be argued that, while capital and labor stocks can be augmented in the future, current economic output is only dependent on the quantities of these factors that currently exist. But the same statement holds for energy and physical resource flows. They are limited by past investment, both in supply and capacity for utilization. Neither can be increased instantaneously beyond fixed limits. The point is that, to a naive observer, energy and material resources are factors of production no less than labor or capital.

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

## Solow's `trinity'

Neoclassical economics, which is the creed taught in most universities and textbooks, depends heavily on three basic assumptions. Robert Solow has allegedly characterized them[1] (tongue-in-cheek, one supposes) as "greed, rationality and equilibrium". By `greed' he apparently means `purposeful behavior', which translates into something like profit maximization (for firms) and "utility maximization" (for individuals.) By `rationality' he means that market actors understand their own preferences and those of others and make optimal decisions based on that understanding. It follows, incidentally, that the theory is timeless, and effectively static, because rationality presumes that each actor in the market can foresee the all the future consequences of each choice and take them into account. This, of course, implies that there are no new possibilities being created as time goes on.

By `equilibrium', of course, Solow refers to the Walrasian theorem that a perfectly competitive free market will reach a Pareto-optimal state in which the supply and demand of every commodity is in balance and the market clears. Pareto-optimality is the situation where nobody can become better off by a trade unless another party is left worse off. It is analogous to the `zero-sum' game postulated by von Neumann and Morgenstern [von Neumann & Morgenstern 1944]. Needless to say, equilibrium in this sense is not the same as thermodynamic equilibrium.

Over the course of decades it has been shown that weaker assumptions with regard to utility maximization and rationality (e.g. `satisficing' instead of optimizing) are sufficient to prove the main theorems, i.e. without losing the most important results of the simpler model. In effect, these developments may be said to have strengthened the standard neoclassical theory by showing that objections based on the unrealism of these two fundamental assumptions do not *ipso facto* invalidate the conclusions, even though some implications may not hold.

On the other hand, the third assumption in Solow's trinity (equilibrium) is a different matter. In the first place, it has not received nearly the same attention as the other two. Most economists, including Solow himself, believe that the economy really is close to a Walrasian equilibrium [e.g. Solow 1970]. For this reason, perhaps, there has been virtually no effort to develop measures of `distance' from equilibrium. In the second place, to give up the equilibrium assumption would automatically invalidate the (implicit) assumption that static optimization with perfect information is tantamount to dynamic optimization. Yet they are not equivalent. This, in turn, invalidates the most popular tool of the modern theorists, namely `constrained optimization' and so-called computable general equilibrium CGE models. We return to this point after a brief digression on neoclassical models.

## Digression on neoclassical growth models

A typical `small' economic forecasting model would consists of a single sector forecasting component or `macro-driver' and a multi-sector I-O module with fixed (or even better, variable) coefficients to reflect the role of (changing) technologies. The macro-driver is typically an aggregate production function of the Cobb-Douglas form with two factors of production, capital K and labor L Technological progress is normally introduced exogenously – under the rubric of `factor productivity' – as an multiplier increasing exponentially at an annual rate of the order of 1.5 percent per annum. Older growth models simply extrapolated historical productivity growth rates.

Sectoral detail was typically introduced by means of a quasi-static Leontief input-output (I-O) module that allocated aggregate demand among individual sectors by means of a matrix of so-called `technology coefficients'. The matrix coefficients were often assumed to be constant (based on empirical relationships already several years old), though some models began to introduce time varying `dynamic' coefficients based on historical trends (e.g. [Leontief *et al* 1977; Leontief & Duchin 1986]).

More recent models mostly incorporate two new features. To modify the essential arbitrariness of the fundamental assumption that factor productivity will continue at historical rates, the notion of `optimal growth' in `general equilibrium', has been promoted. The trick (borrowed from physics) is to introduce a Hamiltonian function of two or three variables– generally the discounted present value of future consumption – that must be maximized subject to as many constraints as required. Maximization involves differentiation with respect to each of the independent variables. Since the number of variables is restricted if the model equations are to be soluble, the I-O structure must be fixed. Hence growth in general equilibrium models essentially means growth in quantitative output (GDP) without structural change, assuming the present I-O structure reflects an equilibrium state (where supply and demand are balanced in all sectors at constant prices).

The implied condition of fixed structural relationships can be modified somewhat, assuming very smooth and gradual changes in some key sector and allowing the others to readjust. However, such models assume either constant technology or exogenous technological change in terms of productivity. They cannot predict, hence cannot accommodate radical innovations (whether technological or other) or rapid changes affecting one or a limited number of sectors, such as may be going on at the present time.

The optimal growth paradigm is that the (discounted) utility of investment in capital for production in the future is balanced against the utility of current consumption. Mathematically, this involves some algebraic relationships between (assumed) discount rates, depreciation rates and marginal utilities of consumption, none of which are directly observable at the macro scale.

Considering the intrinsic technical difficulties, as well as their notorious lack of transparency, general equilibrium growth models have not been especially useful up to now. They are mainly helpful for analyzing a narrow range of near-term policy alternatives where technological change can be neglected (such as implications of a change in the tax regime).

## New approaches in growth theory

To give up the assumption that the economy is always in, or very close to, Walrasian equilibrium essentially means giving up the established theory of economic growth, which attributes a small fraction of economic growth per capita to capital accumulation and the greater part to an exogenous residual known as "technical progress" [Solow 1957]. As it happens, however, the established Solovian theory has been in trouble for some time, for other reasons. It makes two fundamental predictions that do not correspond to the observed facts. One is that the rate of growth of an economy will decline as the capital stock grows, due to declining marginal productivity of capital — a basic postulate of economics. The other prediction (known as `convergence') is that poor countries will grow faster than rich ones.

Recent observations do not confirm either of these predictions. Hence, there has been an explosion of so-called `endogenous growth' theories, based on reinterpretations of capital, weakening of the assumption of declining marginal productivity of capital and weakening or discarding the related assumption of constant returns [e.g. Romer 1986, 1987, 1990; Lucas 1988; Aghion & Howitt 1992, 1998]. There is a lot of interest among theorists in a phenomenon that is quite evident at the micro-scale, namely increasing returns to scale (as exemplified by network systems of all kinds). All of this literature is about models that retain the assumption of growth-in-equilibrium.

But, as mentioned in the introductory section above, there is another sort of evidence that is not consistent with the standard growth theory, and that needs to be taken into account. There exist several identifiable `engines of growth' (i.e. positive feedback cycles) of which the first, historically, and still one of the most powerful, 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 has clearly played a fundamental role in growth since the first industrial revolution. 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 generic energy-power feedback cycle works as follows: cheaper energy and power, due to discoveries, economies of scale and technical progress (learning) in energy conversion, enable goods and services to be produced and delivered at lower cost. This is another way of saying that exergy flows[3] are `productive'. Lower cost, in competitive markets, translates into lower prices for products and services. Thanks to the phenomenon known as 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.[4] This, in turn, stimulates the further substitution of fossil energy and mechanical lower for human (and animal) labor, resulting in further increases in scale and still lower costs. The general version of this Salter cycle is shown schematically in *Figure 1*. There is an obvious specialization to emphasize the role of fossil fuels and other natural resources (stores of exergy).

Based on both qualitative and quantitative evidence, the nature of the positive feedback relationships sketched above imply that physical resource flows have been, and still remain, a major factor of production. Indeed, including a resource 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]. [5]

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.

As it happens, labor gets the lion's share of payments in the 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 (in the US) 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 is not a significant factor of production, or that it can be subsumed in capital, and can be safely ignored.

However, there is a flaw in this too-facile 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 nonsensical. 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.[6] 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.

Energy and material services extracted from the environment are not completely unpaid, of course. Some payments do go to landowners (counted as rents and royalties) and some go to owners of financial capital needed to build machines that dig mines, drill wells, and so forth. Other payments go to miners, oil riggers, and other workers in the extractive industries. Because of the small share of direct payments to natural resource owners in the real national accounts, and based on the above theory of income allocation, most economists have assumed that energy (or, more generally, physical resource inputs) cannot be important factors of production. Here again, there is evidence of under-payment, in the form of a variety of subsidies, either directly (e.g. as depletion allowances or subsidies to consumers), or indirectly as exemptions from paying the costs of environmental damage caused by their activities, or both.

Quite apart from the question of under-pricing, the apparent inconsistency between very small factor payments directly attributable to physical resources – especially energy – and very high correlation between energy inputs and aggregate economic outputs, can be traced to an often forgotten simplification in the traditional 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, changes the picture completely. In effect, downstream value-added stages act as productivity multipliers. Or, to put it another way, the primary sector can be considered as an independent economy, producing value from inputs of physical resources and small inputs of labor and capital. The secondary sector (or economy) imports processed materials from the first sector and uses more labor and capital to produce still higher value products, And so forth. Final consumers receive utility both from small direct inputs of labor and capital and also from value-added by labor, capital and processed exergy from prior stages in the production chain. 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].

The second source of doubt, on the part of many growth theorists, about the importance of resource consumption as a growth driver arises from the fact 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. It is also conceivable that both consumption and growth are simultaneously caused by some third factor. The direction of causality must evidently be determined by other more rigorous means.[7] We argue however, primarily from first principles (see *Figure 1*), that causality is not uni-directional, but bi-directional (i.e. mutual). This has strong implications for the structure of the production function.

## An alternative aggregate long-term production function

It is now convenient to introduce an endogenous production function of the form:

$$(1) \qquad Y = fgB$$

where $Y$ is GDP, measured in dollars, $B$ is a measure of `raw' physical resource inputs (technically, exergy), $f$ 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. The exergy flow $B$ is very nearly the same as the more traditional term $E$, which conventionally refers to energy. Since work appears in both numerator and denominator, its definition is not crucial except for purposes of interpretation. *Note that there is no approximation involved in this formulation, except the tentative assumption that no other factors are involved (i.e. time independence).*

The expression (1) can be interpreted as a production function if (and only if) the product *fg* depends only upon three independent factors of production, viz. labor *L* , capital *K* and exergy consumption *B*. There are two additional conditions to be satisfied. 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, whence 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 they are unlikely to be constant.)

Ideally, we would like to express *f* and *g* in terms of *L,K* and *B* without introducing a time dependent multiplier as Solow did. In practice this may turn out to be difficult. However, since *f* is easily interpreted in terms of exergy efficiency, we can reasonably hope that any time dependence that cannot be explained by the three variables, will have a straightforward physical interpretation (e.g. in terms of information technology.)

Incidentally, the famous *E/GDP* ratio, sometimes called the Kuznets curve, is essentially equivalent to *B/Y*, whence

(2) $E/Y= 1/fg$

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. However, when the exergy embodied in minerals, agricultural biomass and non-commercial fuels (i.e. firewood and charcoal) are included, the supposedly characteristic inverted U shape is much less pronounced, if it exists at all. *Figure 2* shows three versions of the curve. The top curve is the classical Kuznets curve, namely the ratio of fossif fuel exergy to GDP. The middle curve is the ratio of all fuels plus non-fuel exergy, except for agricultural phytomass. to GDP. The peak is much less pronounced. The third and lowest curve is the ratio of total exergy inputs, including agricultural phytomass, to GDP. There is no peak and no inverted U. The inverted U in the top curve apparently reflects the substitution of commercial fuels for non-commercial fuels (wood) during early stages of industrialization.

**Waste generated by the economy**

As noted above, *f* is defined as the ratio of useful work output *U* to exergy *B* embodied in all raw materials extracted from the environment. The exergy embodied in raw materials but not embodied in finished materials is, of course, lost as waste heat or waste materials (pollution), denoted *W*. In fact, it is convenient to introduce a waste term *W* as follows:

(3) $f = (B - W)/B = 1 - W/B$

where both *f* and *W* can be regarded as functions of the three assumed factors of production, *K, L, B*.

What can one say about the loss function *W*? At first glance, one would expect *f* to increase more or less monotonically over time as materials are processed and utilized more and more efficiently. This would imply that $W/B$ declines over time. However, on reflection, $f$ itself is not a pure measure of technical efficiency. On the contrary, $W$ is a composite measure which also reflects the increasing mechanization and electrification of the economy and the fact that converting fossil fuels into mechanical work (and other energy carriers such as gasoline and electric power) involves significant losses.

The trends discussed in the foregoing paragraphs explain why the term $f$ in equation (1) is not a pure measure of conversion efficiency, but rather a reflection of two opposing long-term trends, viz. increasing efficiency on the one hand and increasing demand for performing mechanical work (which includes all uses of electricity) *vis a vis* demand for heat alone, on the other hand. The exergy embodied in finished products can be estimated reasonably well if we assume that `finished materials' consists of all metals and other materials embodied in structures and machines (cement, asphalt, plastic, wood, paper, etc.) plus fuels consumed by households for heating and personal transportation. All other fuels and intermediate materials (e.g. chemicals) are consumed – and converted to waste – in the manufacturing process. The ratio $f$ is plotted for two cases in *Figure 3*. The upper curve reflects the case where total exergy inputs, including agricultural phytomass, are taken into account; the lower curve omits the phytomass. 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.[8]

The next challenge for theory is to explain $f$ and $g$ in terms of the three independent production factors of production, $K, L, B$ excluding time), insofar as possible. Typically both $K$ and $L$ increase over time, but $K$ normally increases faster (if there is growth) and $B$ increases faster still. However, thanks to technical progress GDP increases faster than any of the input factors, including $B$. Evidently the product $fg$ must also be increasing, in the long run (though short term fluctuations are not excluded.) This rules out any Cobb-Douglas type of production function ($Y = AK^aL^bB^{1-a-b}$) or similar functional form unless the multiplier $A$ is time-dependent, *viz.* $A(t)$. This is because economic output $Y$ is growing faster than any of the individual input factors ($K, L, B$), and therefore faster than any product of powers of the inputs with exponents adding up to unity.

The "best" fit (for the Cobb-Douglas case) is actually obtained by choosing $a = 0$ and $b = 0$, whence $Y = AB$. But even in this case $A$ must be a function of time. For purposes of illustration, *Figure 4* shows the familiar Cobb-Douglas function with exponents $a = 0.28$ and $b = 0.68$, leaving an exponent of 0.04 for the exergy term $B$. Obviously economic growth far outstrips the growth of the traditional factors $K$ and $L$. In this case, the technology residual $A(t)$ can be fitted roughly for the entire period 1900-1998 by an approximately exponential function of time (interpreted as a rate of technical progress) which is also plotted in *Figure 4*.

However, there are other functional forms combining the factors $K, L, B$ that may provide better fits. As noted already, the simple form (1) can serve the purpose provided the argument(s) of $fg$ are increasing ratios of the factor inputs, such as $K/L$ or $B/L$. It happens that a suitable functional form (the so-called LINEX function) has been suggested by Kümmel [Kümmel 1982; Kümmel et al 1985], namely

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

(Kümmel equates $E$ and $B$). 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.

In effect, one can make the following approximations, namely

(5) $f = exp\{aL/B\}$

Results of using the LINEX production function for US data from 1900 to 1998 are shown in *Figures 5,6*. for the two exergy cases (including and excluding agricultural phytomass.) In *Figure 7* the unexplained residuals, corresponding to technological progress, are plotted together. Evidently the LINEX function, excluding agricultural biomass leaves the smallest residual. However, it is clear technological progress is not endogenous in any of the three cases. (In future work we will show that the unexplained residual can be explained almost perfectly by introducing U (physical work) into the LINEX production function.)

**Conclusion**

In summary, we argue three theses. The first is that exergy is a major factor of production comparable in importance to labor and capital. The second thesis is that the empirical work/exergy/ratio $f$ is an important measure of technical progress in the long run. Similarly, and third, the output/work ratio g can be regarded as a useful indicator of the extent to which the economy is `dematerializing' (if it is) or `informatizing'[9] in some sense.

Much empirical and statistical work remains to be done to test these three theses, of course. This work is continuing.

## References

Altenpohl, Dieter G. (ed) (1985), *Informatization: The growth of limits* (Series: Report to the Groupe de Talloires), Dusseldorf, Germany: Aluminium-Verlag.

Ayres, Robert U. (2001), ``The minimum complexity of endogenous growth models: The role of physical resource flows", *Energy - the International Journal*(forthcoming).

Ayres, Robert U. & Andrea Masini (1998). 'Waste exergy as a measure of potential harm: Sink-specific exergy measures', in: Ulgiati, S.(ed), *Advances in energy studies: Energy flows in ecology & economy*, Proceeding of a Symposium, Porto Venere, Italy, Proceedings of Symposium, May 23-30, 1998.

Barnett, Harold J. and Chandler Morse (1962), *Scarcity and growth: The economics of resource scarcity*, Baltimore MD: Johns Hopkins University Press.

Beaudreau, Bernard C., *Energy and organization: Growth and distribution reexamined* (Series: Contributions in Economics and Economic History #193)(ISBN 0-313-30580-3), Greenwood Press, Westwood CT, 1998.

Cleveland, Cutler J., Robert Costanza, C. A. S. Hall and Robert K. Kaufmann (1984), 'Energy and the US economy: A biophysical perspective', *Science* **255**, :890-897.

Cleveland, Cutler J., Robert K. Kaufmann and David I. Stern (1998), *The aggregation of energy and materials in economic indicators of sustainability: Thermodynamic, biophysical and economic approaches*, International Workshop on Advances in Energy Studies: Energy Flows in Ecology and Economy, Porto Venere, Italy: May 27-31.

Granger, C. W. J. (1969), 'Investigating causal relations by econometric models and cross-spectral methods', *Econometrica* **37**, :424-438.

Hannon, Bruce M. and John Joyce (1981), 'Energy and technical progress', *Energy* **6**, :187-195.

Kaufmann, Robert K. (1992), 'A biophysical analysis of the energy/real GDP ratio: Implications for substitution and technical change', *Ecological Economics* **6**, :33-56.

Kaufmann, Robert K. (1995), 'The economic multiplier of envirnmental life support: Can capital substitute for a degraded environment?', *Ecological Economics* **12**(1), January :67-80.

Kummel, Reiner (1982), 'Energy, environment and industrial growth', in: *Economic Theory of Natural Resources*, Physica-Verlag. Wuerzburg, Germany:.

Kummel, Reiner (1989), 'Energy as a factor of production and entropy as a pollution indicator in macroeconomic modeling', *Ecological Economics* **1**, :161-180.

Kummel, Reiner, Dietmar Lindenberger and Wolfgang Eichhorn (2000), 'The productive power of energy and economic evolution', *Indian Journal of Applied Economics* **Special Issue on Macro and Micro Economics**, in press. (Also as Kummel, Reiner and Dietmar Lindenberger, Report, University of Würzburg. Würzburg, Germany. 7 April 1998).

Kummel, Reiner, Wolfgang Strassl, Alfred Gossner and Wolfgang Eichhorn (1985), 'Technical progress and energy dependent production functions', *Journal of Economics* **45**(3), :285-311.

Leontief, Wassily W. and Faye Duchin (1986), *The future impact of automation on workers*, New York: Oxford University Press.

Leontief, Wassily W., Ann Carter and P. Petri (1977), *Future of the world economy*, New York: Oxford University Press.

Lucas, Robert E., Jr. (1988), 'On the mechanics of economic development', *Journal of Monetary Economics* **22**(1), July :2-42.

Potter, Neal and Francis T. Christy, Jr. (1968), *Trends in natural resource commodities*, Baltimore MD: Johns Hopkins University Press.

Romer, Paul M. (1986), 'Increasing returns and long-run growth', *Journal of Political Economy* **94**(5), October :1002-1037.

Romer, Paul M. (1987), 'Growth based on increasing returns due to specialization', *American Economic Review* **77**(2), May :56-62.

Romer, Paul M. (1990), 'Endogenous technological change', *Journal of Political Economy* **98**(5), October :S71-S102.

Sims, C. J. A. (1972), 'Money, income and causality', *American Economic Review*.

Smith, H. (1969), 'The cumulative energy requirements of some final products of the chemical industry', *Transactions of the World Energy Conference* **18**(Section E).

Solow, Robert M. (1957), 'Technical change and the aggregate production function', *Review of Economics and Statistics* **39**, August :312-320.

Solow, Robert M. (1970), 'Foreword', in: Burmeister, Edwin and A. Rodney Dobell(eds), *Mathematical Theories of Economic Growth* :vii-ix, MacMillan Company. New York:.

Stern, David I. (1993), 'Energy use and economic growth in the USA: A multivariate approach', *Energy Economics* **15**, :137-150.

von Neumann, John and Oskar Morgenstern (1944), *Theory of games and economic behavior*, Princeton NJ: Princeton University Press.

# Endnotes

1. I haven't identified the original source. It probably doesn't matter.

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]. The immediate conclusion from those empirical results was that scarcity was not in prospect and was unlikely to inhibit economic growth in the (then) foreseeable future. It is also very likely, however, that increasing availability and declining costs of energy (and other raw materials) has been a significant driver of past economic growth.

3. 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).

4. 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.

5. 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.

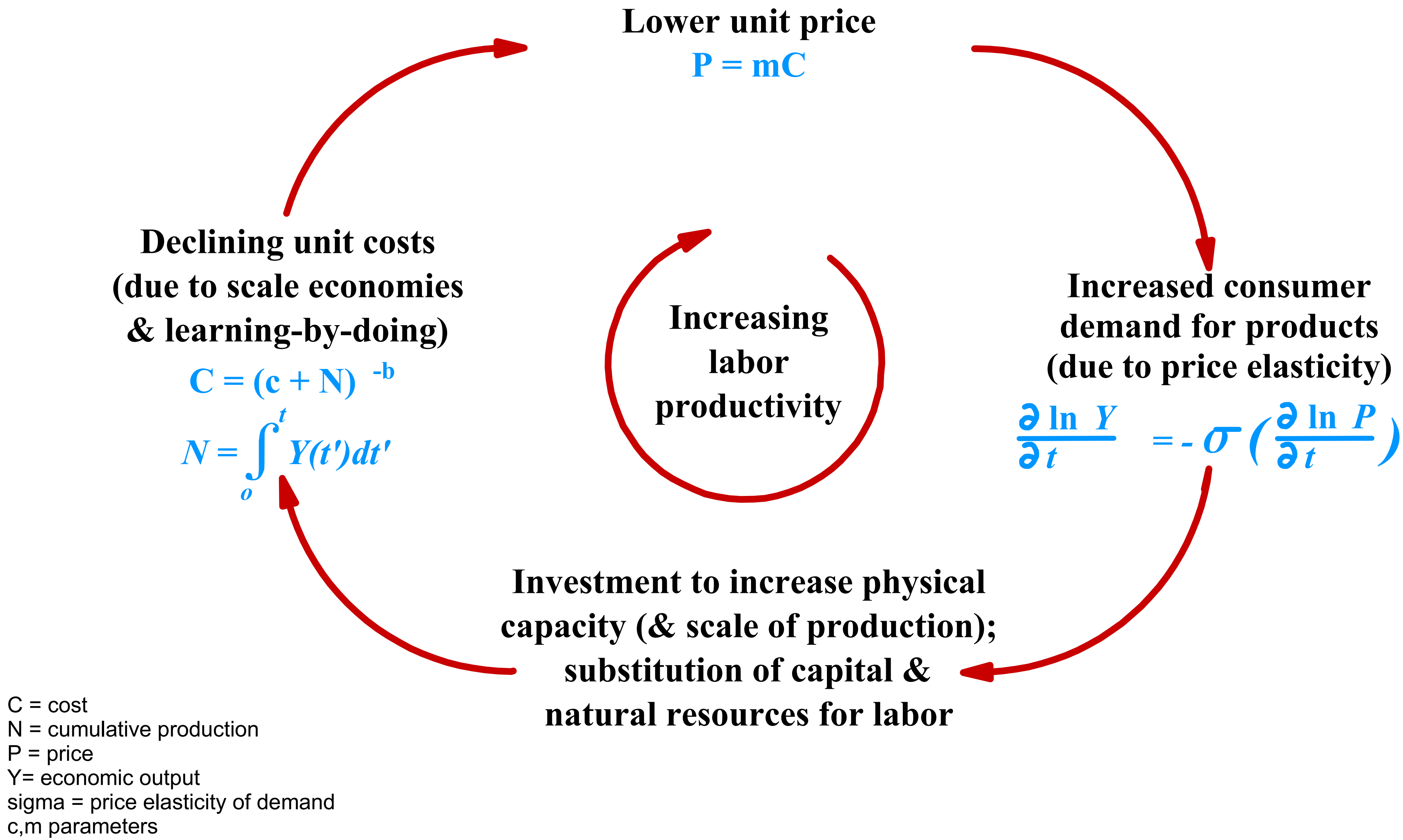
6. In a recently published economic textbook written by a Harvard Professor, the income allocation theorem is `proved' and illustrated using the example of bakeries producing hypothetical bread from capital and labor, but without flour or fuel. Empty calories, indeed!

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. Empirical work is under way, and will shortly be published elsewhere.

9. The term seems to have been introduced by D. Altenpohl [Altenpohl 1985].

**Figure 1: Salter cycle growth engine**



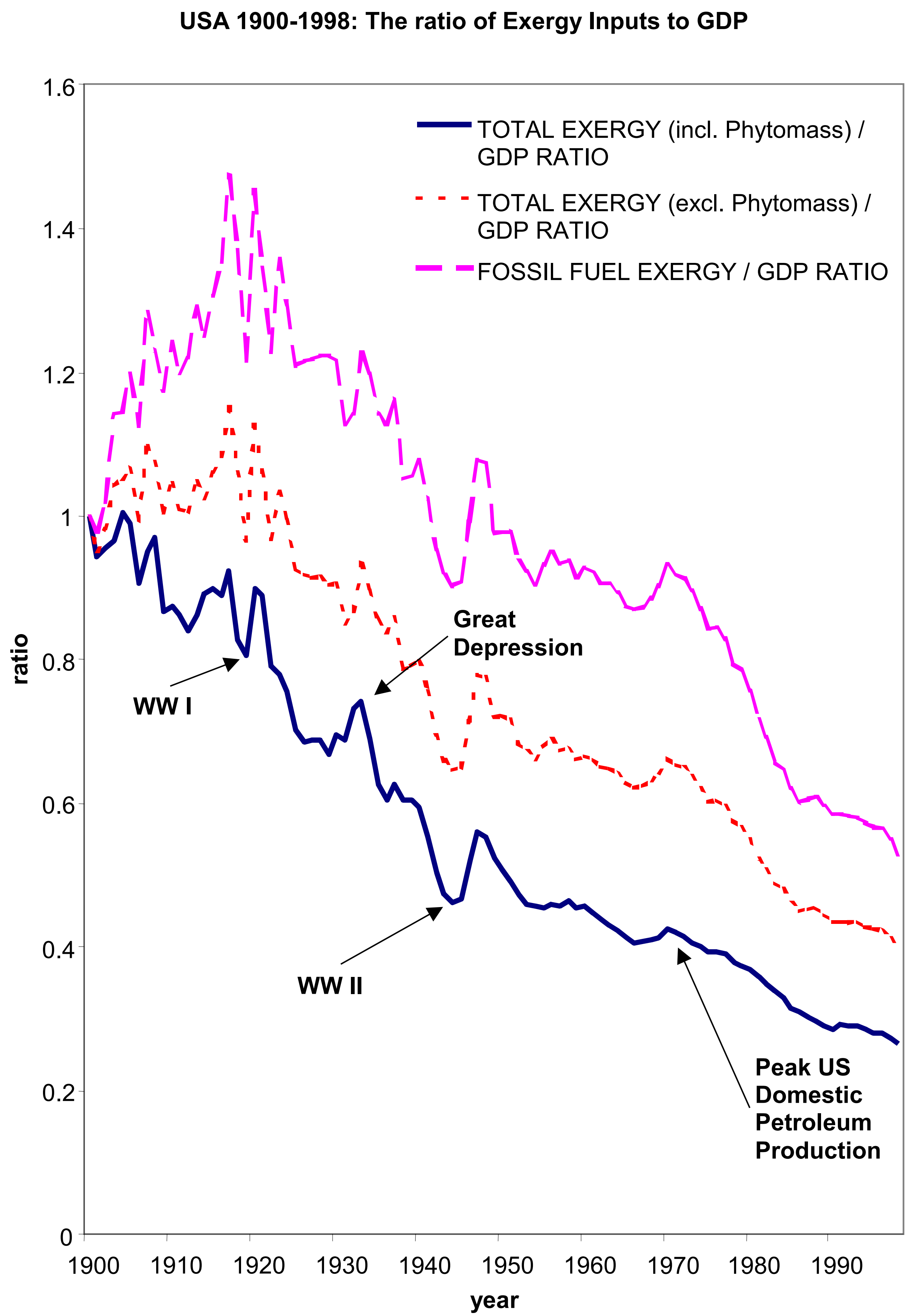



Figure 2. USA 1900-1998 - The ratio of Exergy Inputs to GDP. *Notes:* Calculated using standardised values. Base Year = 1900; Total Exergy 24 eJ; Fossil Fuel Exergy 7.52 eJ; GDP (1992) $ 354 billion.

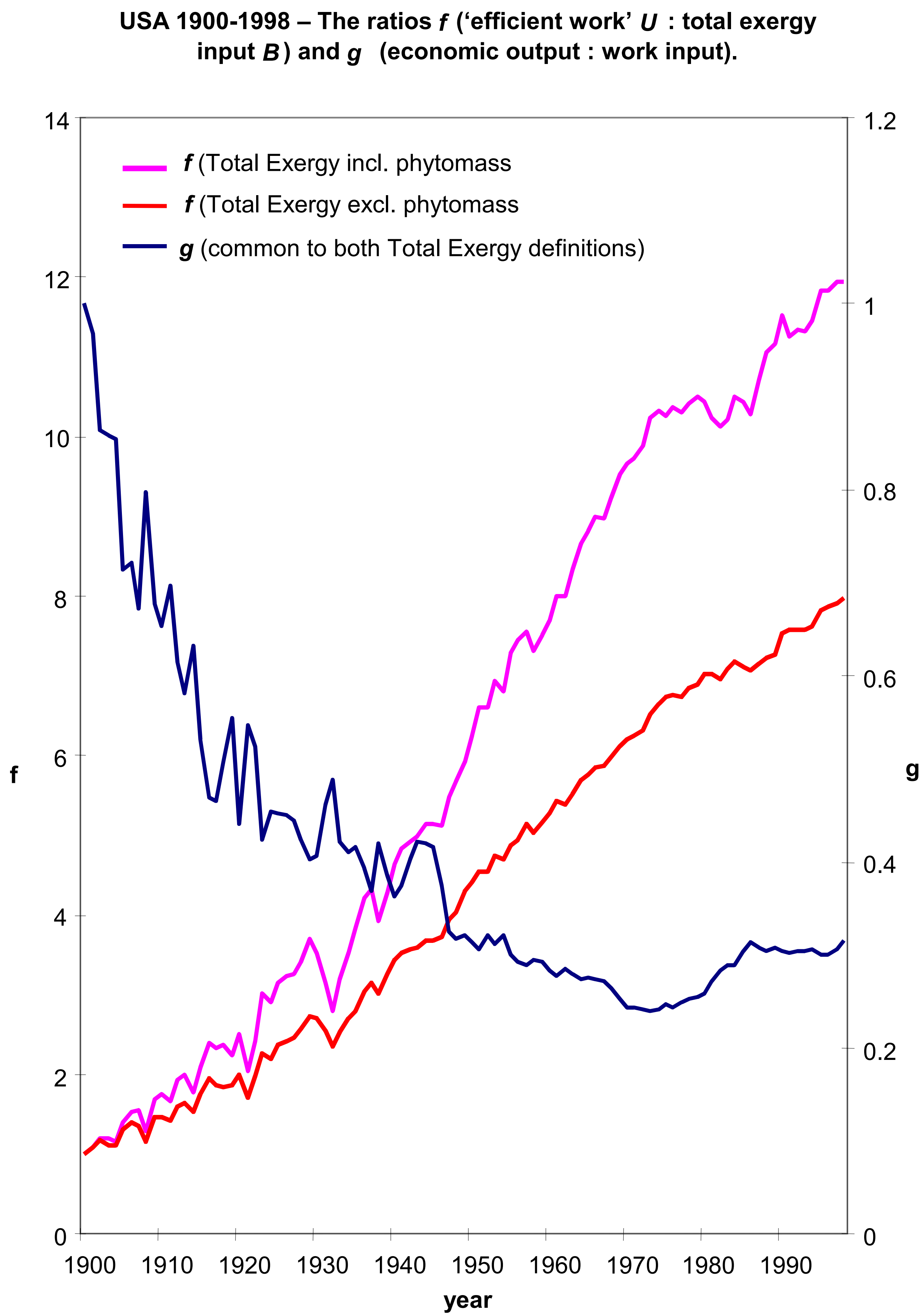



Figure 3 – USA 1900-1998 – The ratios $f$ ('efficient work' $U$ : total exergy input $B$) and $g$ (economic output : work input), calculated using Total Exergy (incl. Phytomass) and Total Exergy (excl. phytomass).

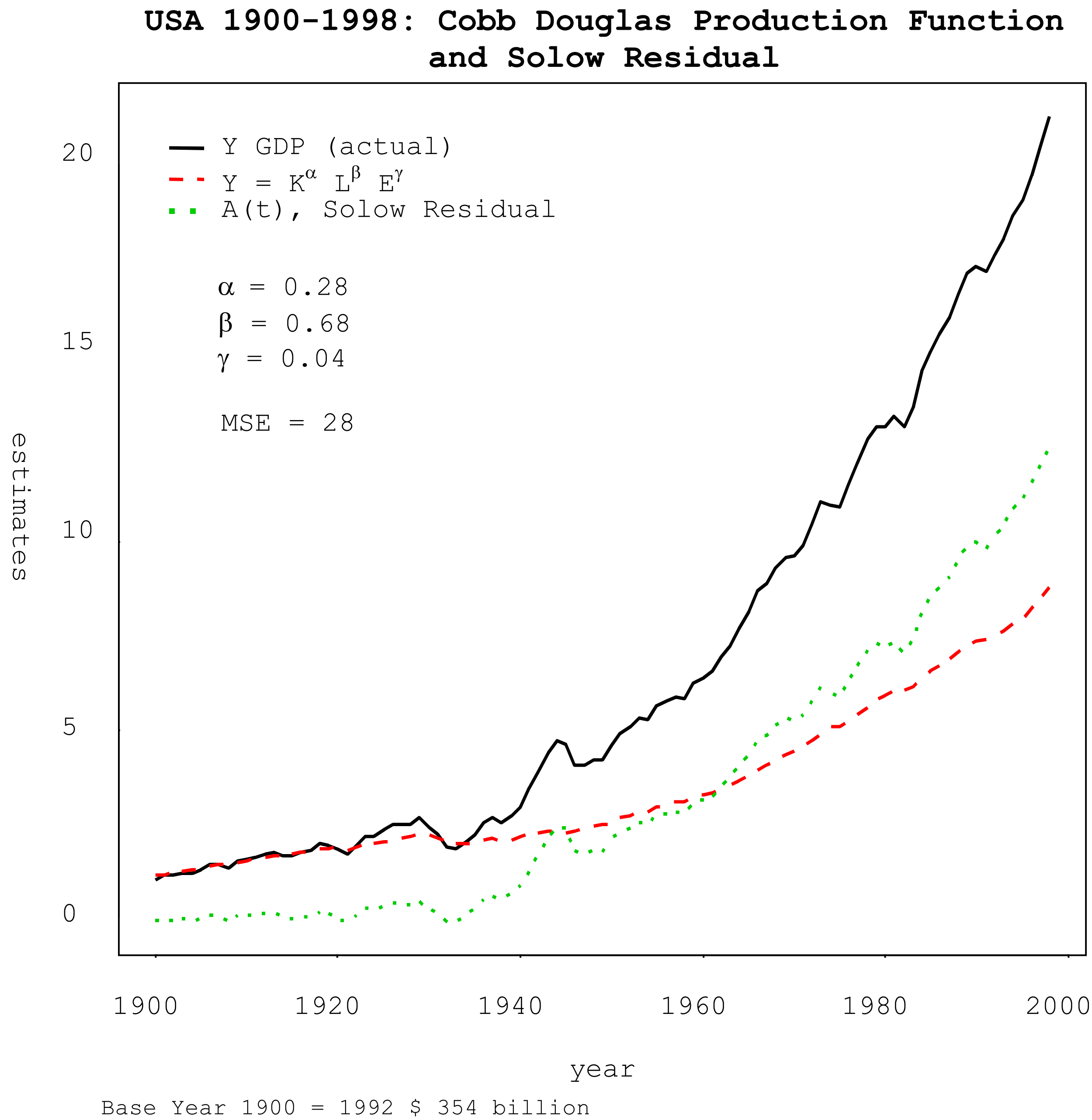



Figure 4. US 1900-1998 'Best-Fitting' Cobb Douglas Production Function (dashed line) and the Solow Residual (dotted line).

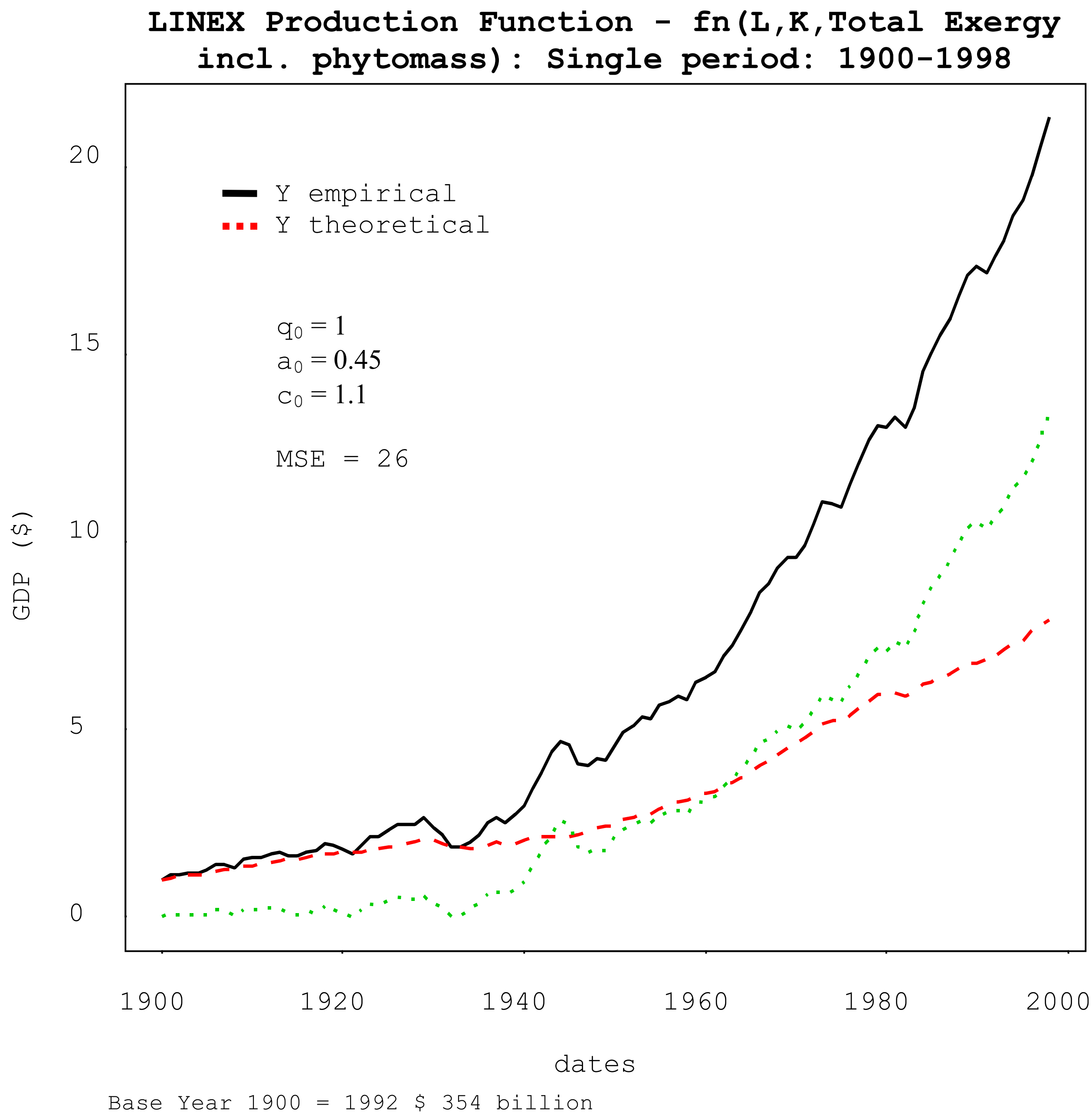



Figure 5. 'Best-fitting' LINEX production function fit by non-linear optimisation over a single time period under the constraint of constant returns to scale ($\gamma = 1 - \alpha - \beta$) using Total Exergy *B* (including phytomass exergy).

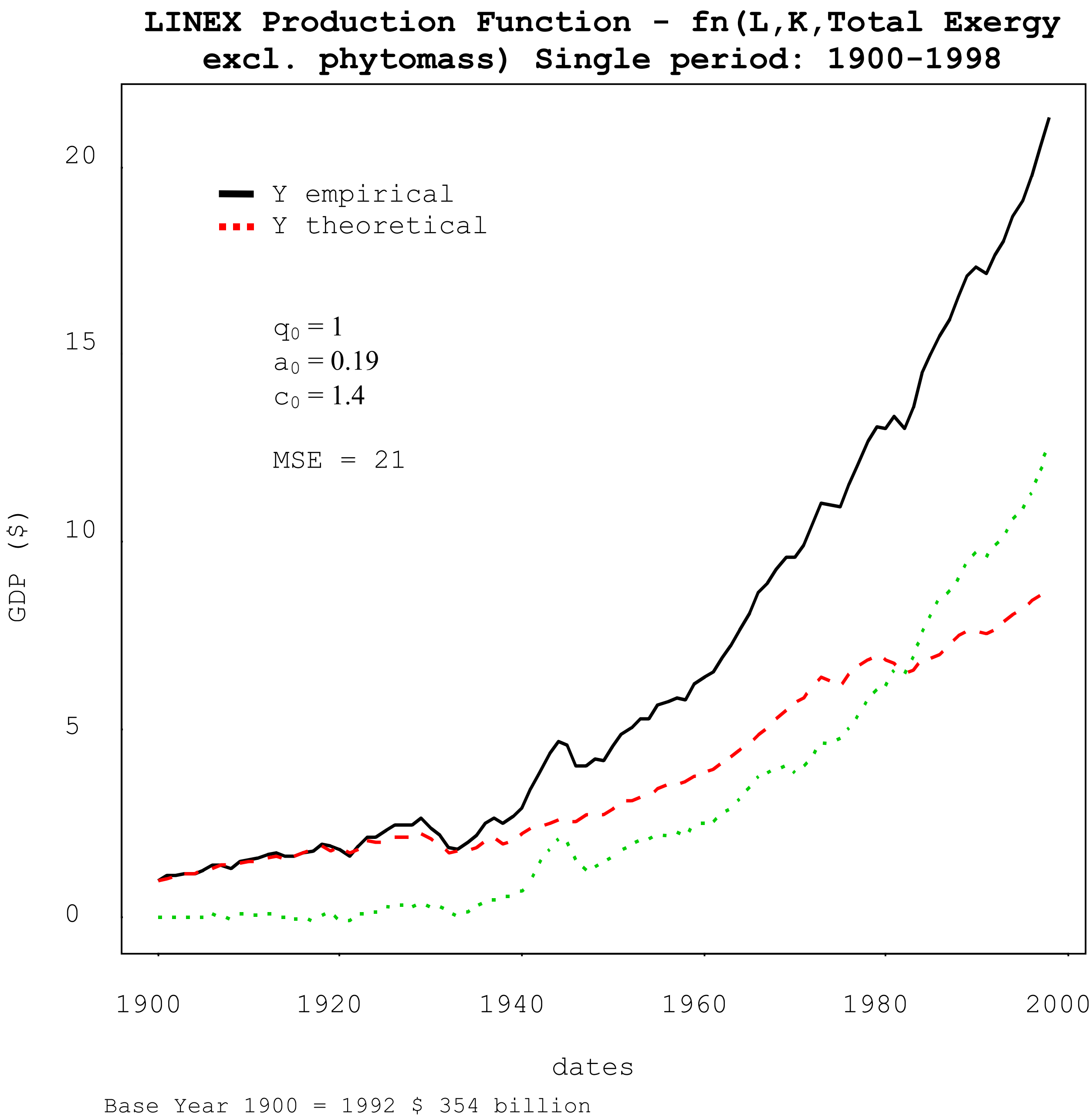



Figure 6. 'Best-fitting' LINEX production function fit by non-linear optimisation over a single time period under the constraint of constant returns to scale ($\gamma = 1 - \alpha - \beta$) using Total Exergy $B$ (excluding phytomass exergy).

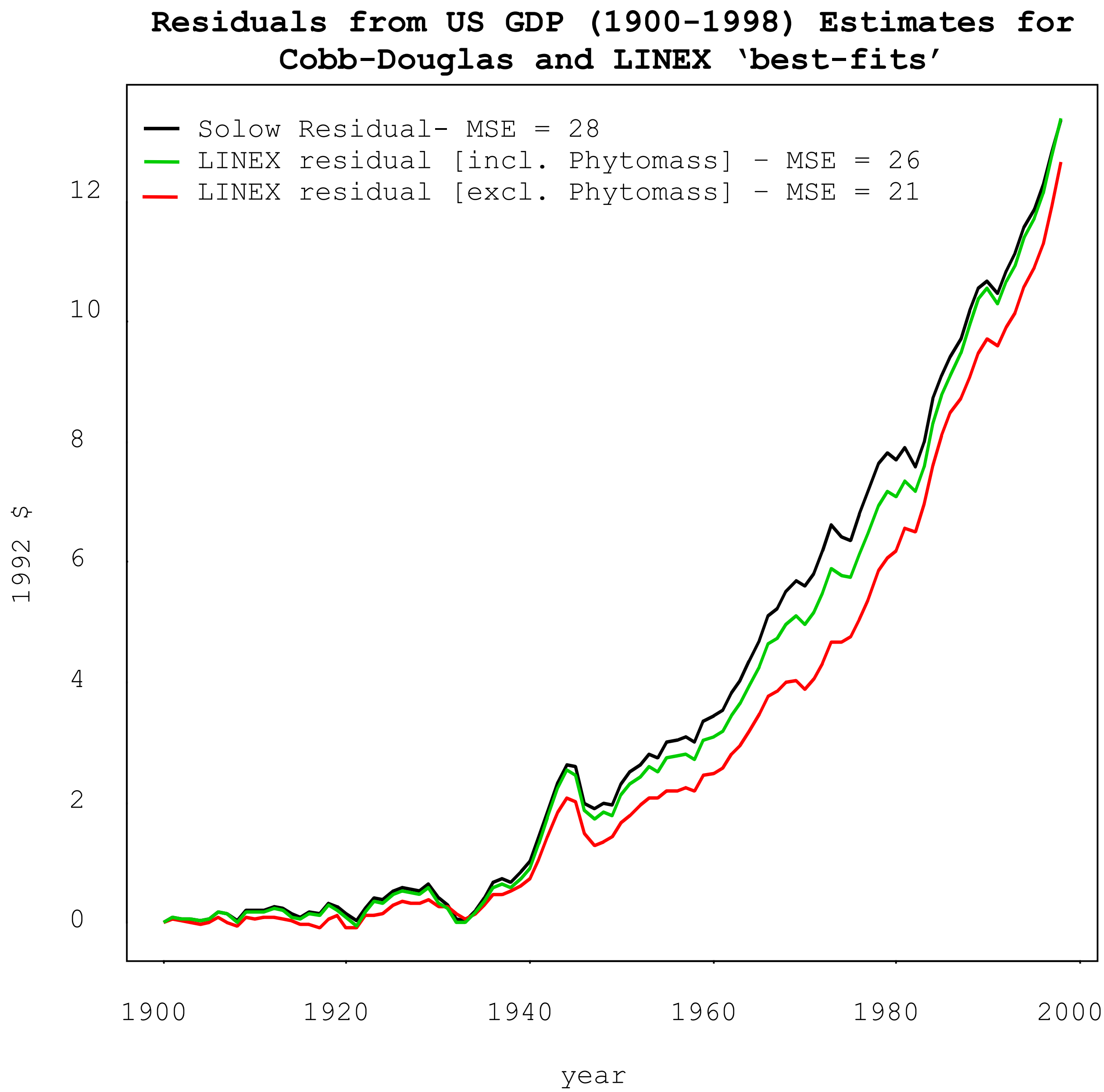



Figure 7. USA 1900-1998: Residuals from estimated GDP, using the Cobb-Douglas and LINEX models with exergy inputs either including or excluding phytomass exergy. (MSE = mean square error).