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The economic growth enigma: Capital, labour and useful energy?

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HIGHLIGHTS

- Economic growth needs three factors of production.
- We propose a semi-parametric generalised production function.
- Exploitation of inexpensive fossil fuel resources has profound policy implications.

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ABSTRACT

We show that the application of flexible semi-parametric statistical techniques enables significant improvements in model fitting of macroeconomic models. As applied to the explanation of the past economic growth (since 1900) in US, UK and Japan, the new results demonstrate quite conclusively the non-linear relationships between capital, labour and useful energy with economic growth. They also indicate that output elasticities of capital, labour and useful energy are extremely variable over time. We suggest that these results confirm the economic intuition that growth since the industrial revolution has been driven largely by declining energy costs due to the discovery and exploitation of relatively inexpensive fossil fuel resources. Implications for the 21st century, which are also discussed briefly by exploring the implications of an ACEGES-based scenario of oil production, are as follows: (a) the provision of adequate and affordable quantities of useful energy as a pre-condition for economic growth and (b) the design of energy systems as 'technology incubators' for a prosperous 21st century.

1. Introduction

The standard (Solow) model and the neoclassical theory of economic growth assume that there are only two important 'factors of production' and that energy and other natural resource inputs contribute very little to the economy, because of their negligible role in the national accounts. This contradicts economic intuition. Economic history suggests that increasing natural resource flows have always been a major factor of production, at least since the large scale exploitation of coal resources in the 18th century. Declining costs of energy – in relation to the rising wages of labour – have induced ever-increasing substitution of machine-work (activated by fossil fuels) for human labour (activated by consumption of grains or fruit). This long-term substitution has evidently been a key driver of economic growth [see also Allen, 2009; Wrigley, 2010, for broadly similar discussions].

The 'real' economy can be thought of as an evolving materials-processing system. The system consists of processing stages, starting with extraction, conversion of energy into useful energy, production of finished goods and services, final consumption and disposal of wastes. An adequate description of the economic system must include materials and energy flows as well as money flows.

These flows and conversion processes are governed by the laws of thermodynamics. At each stage, until the last (consumption), mass-exergy (maximum work performed by energy) flows are split into (i) *useful energy* and (ii) *waste energy* categories. Value is added to the useful energy flows, reducing their entropy content and increasing their exergy content per unit mass (thanks to exogenous inputs of exergy), while the high entropy (low exergy) wastes are returned to the environment. The important point here is that to properly explore the importance of energy in terms of powering economic growth one should use measures of useful energy rather than measures of energy flows or energy carriers such as barrels of oil.

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In view of the assumption by most economists that energy is not a factor of production, the association between primary energy consumption and gross domestic product (GDP) suggests that global energy production is driven by global energy demand, which is driven by global GDP (see Fig. 1). In other words, it is assumed that there are no supply constraints. For purposes of forecasting future energy needs, it follows that a GDP growth forecast, together with a forecast of price and income elasticities, should be sufficient. This is exactly the methodology normally employed in the computable general equilibrium (CGE) models used by the Paris-based IEA (International Energy Agency), the US EIA (Energy Information Administration) and the IMF (International Monetary Fund).

The simplest Cobb–Douglas production function (of capital and labour) takes the following mathematical form:

$$Y_t = A_t K_t^{\alpha} L_t^{\beta} \quad (1)$$

where Y_t is the GDP, K_t is the stock of capital and L_t is the stock of labour, while parameters α and β are constants. Following Solow (1956, 1957), A_t has been interpreted as the effect of 'technical progress' (now called total factor productivity – TFP), which effectively captures the 'unexplained rest' (or the total economic output not caused by capital and labour).

Eq. (1) may also assume that $\alpha+\beta=1$ in order to assure constant returns to scale – doubling capital and labour will also double economic output. Eq. (1) has the convenient mathematical property that output elasticities (logarithmic derivatives) of the two factors of production K_t and L_t are just the constants α and β. Therefore, if we assume *perfect competition* and $\alpha+\beta=1$, α and β can be shown to be labour and capital's (constant) share of economic output respectively.

A theorem taught in macro-economic textbooks postulates a simple economy consisting of many small (price-taking) competing firms producing a single product – such as GDP – from rented capital and rented labour (which are freely substitutable). Then the equilibrium or profit maximising condition requires that total factor requirements must be determined by the marginal productivities of labour and capital. The marginal productivities are the wage rate and the profit rate. Hence, the total payments to labour must be equal to the wage rate times the quantity of labour employed and the total payments to capital must be equal to the profit rate times the quantity of capital employed. In short, the output elasticity of each production factor K_t and L_t must be equal to its cost share in the economic output Y_t, which is equal to the sum total of wages and profits, respectively.

Using standard data series for labour and capital, as Solow did in his early work, explains only a small fraction (ca. 15%) of economic growth. The usual approach is to assume a convenient exponential form for A_t, with a constant annual growth rate of around 2% per annum. This implies that economic growth in the future can be assumed to continue, as in the past. This leaves most of the economic growth on the order of 85%, unexplained. A considerable amount of research effort has been expended on trying to reduce the unexplained residual A_t by introducing quality adjustments to labour and capital. Certainly education and increasing literacy (and numeracy) would be a quality adjustment for labour, while technical performance improvements should also be taken into account for capital goods. Unfortunately none of the proposed adjustments suffice to explain the missing driver.

As an alternative to quality adjustments, we replace the exogenous multiplier A_t by including a third factor of production. Useful energy is not perfectly substitutable for the other two production factors. In effect, we exclude the possibility of producing output from capital alone, or from labour alone, or from useful energy alone. While none of the three factors are a perfect substitute for either of the others, some substitution is possible at the margin. But the range of substitutability is quite limited in reality.

The standard Euler–Lagrange optimization procedure, subject to a mathematical constraint on the possible relationships among the factors, introduces the so-called Lagrange multipliers, i.e. 'shadow prices' of the constraints. If the constraints are not binding, the shadow prices will be zero, in which case the cost share theorem will still hold as if there were no constraints. But what if substitutability between the factors is much more limited than most economists assume? If this is so then the output elasticity of useful energy must be much larger than its cost share (as normally calculated as revenues of energy companies).

If the output elasticity of useful energy is greater than its cost share, it follows that energy is really more productive than its price suggests. In other words, useful energy is under-priced. In that case, the optimum (profit-maximizing) consumption of useful energy in the economy is actually larger than current consumption. Can this possibly be true? Most economists will say 'no' because otherwise the traditional cost-share theorem must be discarded.

In fact, there is plenty of empirical evidence that firms actually use too much useful energy, rather than too little (this is consistent with under-pricing). Firms consistently neglect cost-saving investments in energy conservation, with very high returns, in favour of investments in marketing, new products or capacity expansion. Governments and consumers behave in roughly the same way, preferring to spend on current consumption rather than investment in future cost savings. However, the fact that many firms use more useful energy than they could does not mean that the national economy could not be more productive (by using more capital and less labour where substitution is possible).

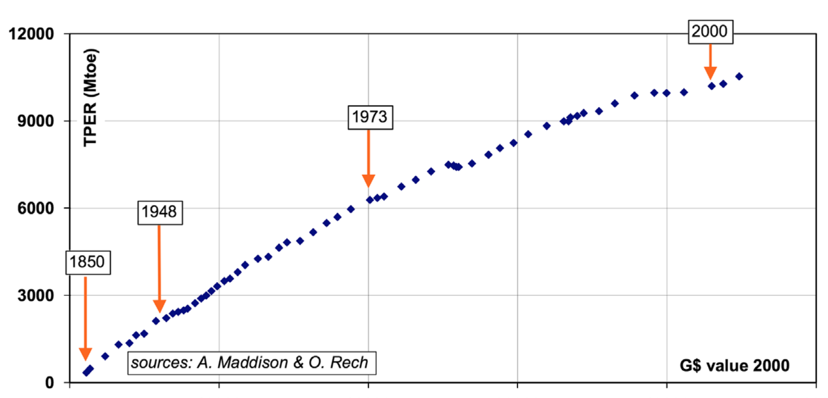

Fig. 1. World TPER versus GDP PPP 1850–2002.
Source: Bourdaire, "Drivers of the Energy Scene", World Energy Council Report 2003. Graph I-1. Data from A. Maddison and O. Rech.