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Capital, labor, energy and creativity: modeling innovation diffusion☆

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Abstract

Economic growth in the USA, Japan, and Germany during three decades and the recessions during the energy crises are well reproduced by production functions that depend on capital, labor, energy and three technology parameters. Time changes of these parameters model innovation diffusion, driven by creativity. In all three countries the time-averaged elasticities of production of energy exceed the share of energy cost in total factor cost by about an order of magnitude, and those of labor are much less than labor's cost share. Only for capital, elasticities and shares are roughly in equilibrium.

JEL classification: E23; O31; O57; Q43

Keywords: Work; Information; Elasticities of production; LINEX production function; Innovation; Economic growth

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1. Introduction: energy crises

In 1973 the OPEC cartel, responding to the Jom-Kippur war, and in 1979 Saddam Hussein, attacking revolutionary Iran, triggered the first and the second oil-price explosions: The price of a barrel of crude oil jumped from 10 US $ in 1973 to about 30 $ in 1975, and from that level it went up to over 55 $ between 1979 and 1981 (all prices in constant US $ of 1993). In a shock-reaction many industrial market-economies reduced energy utilization drastically. This led to an economic experience of paramount importance: in countries like the USA, Japan, and Germany the reduction of industrial output closely followed the reduction of energy input during the first oil-price explosion, and there was a world-wide recession, *the energy crisis*. The impact of the second price hike was still substantial, but it was softened by the decisions of governments and entrepreneurs to introduce energy conserving and non-fossil fuel technologies into the capital stock as a response to the first oil-price explosion. Unfortunately, these efforts, and the supporting research, declined when the oil price plummeted to 20 $ in 1985, fluctuating around that level until 1992, after which year it went further down to about 11 $ in mid-1999. People got used again to wasting cheap energy. Thus, when the oil price nearly tripled until mid-2000, they went into another shock, and governments had to deal with civic unrest. The protesters demanded the reduction of energy taxes. These taxes have been raised over the years by governments of different political orientation in order to provide the state with another source of income. In addition, a growing minority of citizens considers a gradual increase of taxes and levies on energy use and a simultaneous reduction of taxes and levies on labor as appropriate measures to stimulate energy conservation, the market penetration of non-fossil energy technologies, emission mitigation and the reduction of unemployment. For instance, in the debate on greenhouse-gas emissions 2000 American economists, in their Economists' Statement on Climate Change (1997), declare that "the U.S. and other nations can most efficiently implement their climate policies through market mechanisms such as carbon taxes or the auction of emission permits. The revenues generated from such policies can effectively be used to reduce the deficit or to lower existing taxes". Similarly, the Energy Memorandum of the German Physical Society (1995) recommended that "prices for the use of energy must be raised stepwise on the basis of dependable long-term planning to a point where technologies for efficient energy usage and non-fossil energy resources can survive in the market against the conventional combustion of fossil fuels". But the economic and scientific rationale for such fiscal policy is convincing voters only slowly, and although the recent unrest died down with the decline of the oil price to about 22 $ in January 2001, it clearly showed the still strong opposition of many people against self-imposed constraints on energy use.

The unpleasant social and economic reactions to sudden energy-price increases are quite understandable: people worry that they may no longer enjoy the cheap services of the energy slaves that have provided the material wealth, comfort, and mobility in the industrial countries. Here, the number of energy slaves is given by the average amount of energy fed per day into all the man-made energy-conversion devices of a country, divided by the daily human work-calorie requirement of 2500 kilocalories (= 2.9 kWh) for very heavy work load. Thus, in 1995, when the consumption of primary energy per day and person was 270 kWh in the USA and 133 kWh in Germany, there were about 90 energy slaves serving every American and 45 serving every German; and they cost so little: In the OECD countries just about 5% of the total factor cost in production and about the same percentage in household expenditure fall to the share of energy (Baron, 1997).

Since energy has been so cheap; neoclassical economists consider it as a production factor of only marginal importance. According to the neoclassical model, built in analogy to 19th-century classical mechanics, the economy evolves in a state of equilibrium characterized by a profit maximum, which lies in the interior—and not on the boundary—of the factor space accessible to the production system according to its state of technology. Then, a marginal change of output due to a marginal change of a given input would be equal to the market price of one unit of that input, and the elasticity of production of energy, which, roughly speaking, measures the percentage change of output when the input of energy changes by 1%, should be just 0.05. As a consequence, according to the neoclassical model, reductions of energy input by up to 7%, observed during the first energy crisis, could have only caused output reductions which are by an order of magnitude smaller than the actually observed ones of up to 5% (Denison, 1979), and the economic downturns, slowdowns and upswings in the wake of the first two oil-price explosions remain unexplained.

Furthermore, a substantial part of observed long-term economic growth cannot be reproduced by the growth rates of the production factors, if these are weighted by the factor-cost shares. (Typically, in highly industrialized countries, these shares are in the range between 25 and 30% for capital and 70 and 75% for labor.) Large residuals remain. They are attributed to what is called 'technical progress'. This progress is formally taken into account by introducing a time-dependent multiplier in the aggregate production function (Solow, 1957). It is measured by determining the parameters related to the time-dependency of the production function (Krelle, 1986; Badke, 1990) and classified according to neutrality hypotheses, e.g. Hicks, Harrod, Solow, Beckmann-Sato neutral technical progress (Stehling, 1978). Up to 70% of growth in industrial countries are attributed to technical progress by recent analyses. (For a review see Boskin and Lau (1992).) Thus, the residuals often play a more important role than the explanatory factors, which in most cases are capital and labor. In response to these findings the concept of technical progress has been intensively debated. According to Gahlen (1972) it makes the neoclassical theory of production tautological. Solow, after noting "... it is true that the notion of time-shifts in the [production] function is a confession of ignorance rather than a claim of knowledge" (Solow, 1960), comments: "This ... has led to a criticism of the neoclassical model: it is a theory of growth that leaves the main factor in economic growth unexplained" (Solow, 1994). Recently, within the 'New Growth Theory' (Romer, 1986; Lukas, 1988) a variety of approaches to explain technical progress and growth have been put forward. Howard Pack's (1994) conclusion is: "But have the recent theoretical insights succeded in providing a better guide to explaining the actual growth experience than the neoclassical model? This is doubtful".

In view of the open questions of neoclassical theory, and contemplating that—according to the first and second law of thermodynamics—nothing happens in the world without energy conversion and entropy production, and expecting that—because of political conflicts, economic mismanagement and/or the environmental and resource constraints resulting from entropy production—energy prices will increase in the future until a backstop technology provides energy from nuclear fusion in the Sun and on Earth, it seems to be worth-while to investigate more in detail the role of energy in economic production and growth. Simultaneously one must look into the technological changes brought about by human creativity and innovation diffusion that widen the application of energy and enhance the efficiency of its use. The present article tries to quantify the economic effects of energy and creativity in five case studies for three major industrial countries. It continues earlier attempts to respond in part to "the need to reintegrate the natural sciences with economics" (Hall et al., 2001). These attempts analyzed the growth of the industrial sectors in the USA, Japan and Germany with piecewise static versions of a new class of production functions, called LINEX functions. They resulted in residuals much smaller and elasticities of production of energy much higher than in neoclassical theory. Now we develop dynamic versions of the LINEX function by allowing for continuous, explicit time dependencies of their technology parameters. Applying the new functions to the industrial sectors considered before we find that the improved modeling of technological change further reduces the residuals without altering significantly the previous findings that energy is much more important to production and growth than neoclassical theory assumes.

In addition, LINEX analyses, based on novel data for the total economies of the USA from 1960 through 1996 and of the Federal Republic of Germany from 1960 through 1989, show that the economic weight of energy remains high above its cost share even when all service sectors are included in the econometric analysis. We hope that, by elucidating the economic role of energy in conjunction with creativity, the present work may contribute somewhat to the search for instruments to implement the proper structural changes that are required for maintaining economic dynamics on a path of sustainable growth.

2. Aggregation and production factors

We use a capital-labor-energy-creativity (KLEC) model of economic production and growth. This model avoids the neoclassical equilibrium assumption of the equality of elasticities of production and cost shares (Kümmel, 1980, 1982, 1989; Kümmel et al., 1985, 1997, 2000; Lindenberger et al., 2000). It is a child of thermodynamics and economics. Energy, revealed as the fundamental driver of change by thermodynamics, is investigated with respect to its economic power, and, methodologically, the model aims at a simple, quantitative, phenomenological description of economic evolution by production functions that depend on empirical data from the national accounts, labor statistics and energy balances; similarly, thermodynamics describes complex, interacting many-body systems with the help of state functions like entropy that depend on given quantities such as temperature and volume. And as in thermodynamics the heterogeneous system components are aggregated according to the relevant basic features they have in common. In the case of industrial economies these features are work performance and information processing: energy conversion in the human body and in the machines and other energy conversion devices of the capital stock provides the work that (a) moves masses and erects structures, (b) arranges the atoms of the raw materials in the order required for the finished products, and (c) drives the electrons in the electric devices of the goods-producing and service industries. Information in the form of energy signals and their modulation, processed in the brain and nervous system of humans and in the transistors and other switching devices of the capital stock, controls the flow of work during the production of goods and services. Every purposeful activity requires work performance and information processing.

Capital K, labor L and energy E are the physical factors of production that generate the industrial output Q by work performance and information processing. L and E are measured by manhours worked and energy quantities, e.g. Joules, utilized per year. (Strictly speaking, the production factor E is really *exergy* consumption. Exergy is the valuable part of energy that can be converted into any other form of energy, especially work. The principal fossil and nuclear energy carriers which make up E are practically all exergy.) The technical definitions and measurement prescriptions of Q and K are given in Kümmel (1982), Kümmel et al. (2000) and the Internet Supplement.[1] Especially important is the understanding that the capital stock consists of all energy-conversion devices and the installations and buildings necessary for their operation and protection. This allows an aggregation of the inhomogeneous capital goods in terms of their capacity of delivering power and process information. This capacity is the basis of all automation. Its unit is called the ATON.[2]

Capital, labor and energy are independent variables in the sense that within technological limits entrepreneurs can vary them independently according to their decisions on the capital stock's quantity (more or less of the same) and quality

[1] http://theorie.physik.uni-wuerzburg.de/TP1/kuemmel/profile.html.

[2] This unit (of AuTomatiON) is defined as 1 ATON = 1 kW $\times\ \kappa$ kilobits/s. The average equivalence factor κ is given by $\kappa = (1/N)\,\Sigma_{i=1}^{N} S_i T_i$, where the definitions of N, S_i and T_i imply the measurement prescription of the ATON: K is partitioned in $N \gg 1$ pieces K_i, which all have the same monetary value, say v EUROs. Then S_i = number of kilowatts performed, and T_i = number of kilobits/s processed by the fully employed ith capital good K_i. As a consequence of these definitions the ATON value of K, A_K is proportional to the monetary value of K, M_K, shown in the national accounts in constant currency, as long as κ stays constant: $A_K \equiv N$ ATONs $= \Sigma_{i=1}^{N} S_i T_i$ kW $\times$ kB/s. $M_K \equiv Nv$ EUROs, thus $A_K = (M_K/v)$ (ATON/EURO). Changes of κ occur when the monetary valuation of the capabilities of work performance and information processing changes. The capital services of performed work and processed information flow from the capital stock to the same extent as energy and labor activate and control that stock. An equivalence factor ζ, similar to κ, appears in the technical definition of output Q in terms of the physical work performed and the number of information units processed in its generation.

(more or less automation) and the degree of capital utilization: variations of labor and energy at constant quantity and quality of capital are associated with variations in the degree of capital utilization, changes in automation change the relative magnitude of the labor and energy inputs that are required to handle and activate capital at a given degree of capital utilization, etc.

Raw materials neither perform work nor process information. They are the passive partners of the production process. Their atoms or electrons are just rearranged by capital, labor and energy into the configurations or flows required for a product or service. Thus, they do not contribute actively to the generation of value added, and their monetary value is not included in the national accounts' empirical time series on value added. In computing the growth of output they may be disregarded as long as the finiteness of their resources does not result in growth constraints.[3] Similarly, land, or rather its three-dimensional extension 'space', may be disregarded too, as long as the finite emission-absorbing capacity of the biosphere does not result in limits to growth.

Finally, the factor that may pass unnoticed in the short run but will be decisive in the long run is *creativity*, i.e. the specifically human contribution to economic evolution that cannot be made by any machine capable of learning. It consists of ideas, inventions and value judgements and causes the explicit time dependence of the production function

$$q = q[k(t), l(t), e(t); t] \tag{1}$$

we will employ in order to describe economic growth.[4] Here $q(t) \equiv Q(t)/Q_0$, $k(t) \equiv K(t)/K_0$, $l(t) \equiv L(t)/L_0$ and $e(t) \equiv E(t)/E_0$ are the output and the production factors at time t normalized to their numerical values Q_0, K_0, L_0, E_0 in a base year. (In the normalized variables of output and capital the constants of proportionality between the technological and the monetary values drop out as long as the equivalence factors stay constant in time.)

Macroeconomic production functions are an instrument widely used in neoclassical economics. The Deutsche Bundesbank (1996) employs them for computing the gross domestic product of the USA, Japan, Germany and others from 1974 to 1995.

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[3] In systems, where catalytic processes play a quantitatively important role, one might consider treating the catalytic materials as a factor distinct from the capital stock.

[4] Macroeconomic production functions have been criticized, recently especially by Kurz and Salvadori (1995), Kurz (2000). It is said that the endowment of the economy with heterogeneous capital goods cannot generally be given in terms of a scalar-valued magnitude, which is taken to be independent of the rate of interest and relative prices (Kurz, 2001). However, as we have shown, the seemingly heterogeneous capital goods can be homogenized by the technological definition and measurement prescription of instrumental capital in terms of the ATONs. Furthermore, Schmalwasser (2001) of the Statistisches Bundesamt Wiesbaden confirms: (a) the gross capital stock at constant prices is indeed a measure of the capacity of work performance and information processing. (b) Fluctuations in interest rates play no role in the determination of the volume of produced capital goods; they are only relevant, if the coupling to the financial sphere of money capital is part of the analysis. (c) Fluctuations in prices are taken into account properly in the time series of gross capital stock, because the computations are based on the investments in prices of a base year.

We leave the realm of neoclassical economics on the way of calculating the production functions.

3. Growth dynamics

We relate the marginal change of (normalized) output, dq, to the marginal changes of (normalized) capital, dk, labor, dl, energy, de, and time, dt, by the total time derivative of the production function (1), divide this derivative by q, multiply it by dt and obtain the 'growth equation':

$$\frac{\mathrm{d}q}{q} = \alpha\,\frac{\mathrm{d}k}{k} + \beta\,\frac{\mathrm{d}l}{l} + \gamma\,\frac{\mathrm{d}e}{e} + \delta\,\frac{\mathrm{d}t}{t}, \tag{2}$$

with the abbreviations,

$$\alpha(k, l, e) \equiv \frac{k}{q}\frac{\partial q}{\partial k}, \quad \beta(k, l, e) \equiv \frac{l}{q}\frac{\partial q}{\partial l}, \quad \gamma(k, l, e) \equiv \frac{e}{q}\frac{\partial q}{\partial e}, \quad \delta \equiv \frac{t}{q}\frac{\partial q}{\partial t}. \tag{3}$$

The quantities defined by Eq. (3) are the *elasticities of production*. They give the weights by which the marginal relative changes of the production factors and of time contribute to the marginal relative change of output. In this sense they measure the productive powers of capital, labor, energy, and creativity. It is in the further treatment of these weights by which our model deviates from the growth models of neoclassical economics.

Econometric experience shows that in economic models the specifically human influence cannot be disregarded for more than 10–20 years; in the course of time there will be structural changes and the characteristic parameters of the model will no longer stay constant (Rinne, 1976; Hübler, 1989). This suggests to design a model with technology parameters that are constant, when creativity is dormant, and that change in time, when creativity induces structural changes, e.g. in response to especially challenging events. The oil-price explosions were such events (Leiner, 1998).

If the creativity term δ is negligibly small, capital, labor and energy are the only active factors of production. Thus, the production function must be linearly homogeneous in k, l, e, i.e.

$$\gamma = 1 - \alpha - \beta. \tag{4}$$

Then,

$$\alpha = a\,\frac{l+e}{k}, \quad \beta = a\left(c\,\frac{l}{e} - \frac{l}{k}\right) \tag{5}$$

are technologically reasonable, simple factor-dependent solutions of the three coupled differential equations that result from the requirement that the second order mixed derivatives of q with respect to k, l, e must be equal (Kümmel, 1982).[5]

[5] The differential equation for α is $k(\partial\alpha/\partial k) + l(\partial\alpha/\partial l) + e(\partial\alpha/\partial e) = 0$, the equation for β has identical structure, and the coupling equation reads $l(\partial\alpha/\partial l) = k(\partial\beta/\partial k)$.

If creativity is active, the technology parameters a and c become time dependent. The integral of the growth equation (2) with α, β and γ from Eqs. (5) and (4) is the time-dependent (first) LINEX production function,

$$q_{\mathrm{Lt}} = q_0 e \exp\left[a(t)\left(2 - \frac{l+e}{k}\right) + a(t)c(t)\left(\frac{l}{e} - 1\right)\right], \tag{6}$$

which depends linearly on energy and exponentially on quotients of capital, labor and energy. (More complicated elasticities of production result in higher LINEX functions (Kümmel et al., 1985; Lindenberger, 2000).) Only such factor combinations make sense economically for which the elasticities of production α, β and γ are non-negative. For more details see the Internet Supplement. Time-changing $a(t)$ and $c(t)$ imply $\delta = (t/q)\,(\partial q_{\mathrm{Lt}}/\partial a)(\mathrm{d}a/\mathrm{d}t) + (\partial q_{\mathrm{Lt}}/\partial c)(\mathrm{d}c/\mathrm{d}t)$.

The mathematical structure of α reflects the law of diminishing returns, and the capital-efficiency parameter a gives the weight with which labor/capital and energy/capital combinations contribute to the productive power of capital. The form of β allows for an approach to the state of total automation in the sense that the energy-demand parameter c indicates the energy demand $e_{\mathrm{A}} = ck_{\mathrm{A}}(q_{\mathrm{A}})$ of the fully utilized capital stock $k_{\mathrm{A}}(q_{\mathrm{A}})$ that would be required in order to generate the part q_{A} of output accessible to totally automated production with virtually no labor, while the production of $(q - q_{\mathrm{A}})$ is labor saturated; then β goes to zero as e and k approach e_{A} and k_{A}. The integration constant q_0 measures the average monetary valuation of the original basket of goods and services making up the output unit Q_0.

4. Case studies: USA, Japan, Germany

We have applied the KLEC model to the sectors ‘Industries’ of the USA and Japan and the West German industrial sector ‘Warenproduzierendes Gewerbe’. These sectors, for which consistent sets of data could be obtained, produce about 85, 90, and 50% of gross domestic product, respectively. The annual empirical values of q, k, l, e, available to us for the USA from 1960 to 1993, Japan from 1965 to 1992, and West Germany from 1960 to 1989, are used when the LINEX function is fitted to the empirical output data. The non-linear fitting procedure under the constraints of non-negative elasticities of production α, β and γ is performed with the help of the Levenberg–Marquardt method of non-linear optimization (Press et al., 1992). For analyses of the past we disregard the growth constraints that are due to entropy production.

We first summarize results obtained previously by modeling creativity’s action in rather simple ways (Lindenberger, 2000; Kümmel et al., 2000; Hall et al., 2001). (i) With constant q_0, a and c, i.e. neglecting creativity altogether, one can reproduce the empirical growth in Japan and Germany during the full observation times with residuals less than 10%. (ii) Fitting the LINEX function $q_{\mathrm{Lt}} \equiv q_{\mathrm{theoretical}}$ to the empirical time series of output with one set of constant parameters q_0, a and c until 1977 and determining another set of constant q_0, a and c by fitting to the data after 1978 yields annual theoretical outputs $q_{\mathrm{theoretical}}$ that, in general, reproduce well economic growth in all three considered systems, including the downturns and upswings during and after the first and second energy crisis; only in 'USA, Industries' $q_{\text{theoretical}}$ stays systematically below $q_{\text{empirical}}$ after 1984. The time-averaged elasticities of production, i.e. the productive powers of capital, $\bar{\alpha}$, labor, $\bar{\beta}$, and energy, $\bar{\gamma}$, are computed by inserting the k, l, e, given by the time series in Figs. 1–3, and the corresponding a and c into Eqs. (4) and (5); then the elasticities of production of capital, labor and energy are averaged over the total observation times. We find: (a) for the USA, $\bar{\alpha}=0.36$, $\bar{\beta}=0.10$, $\bar{\gamma}=0.54$; (b) for Japan, $\bar{\alpha}=0.34$, $\bar{\beta}=0.21$, $\bar{\gamma}=0.45$; and (c) for West Germany, $\bar{\alpha}=0.45$, $\bar{\beta}=0.05$, $\bar{\gamma}=0.50$. The order of magnitude of the errors is ± 0.1 (Lindenberger, 2000).[6]

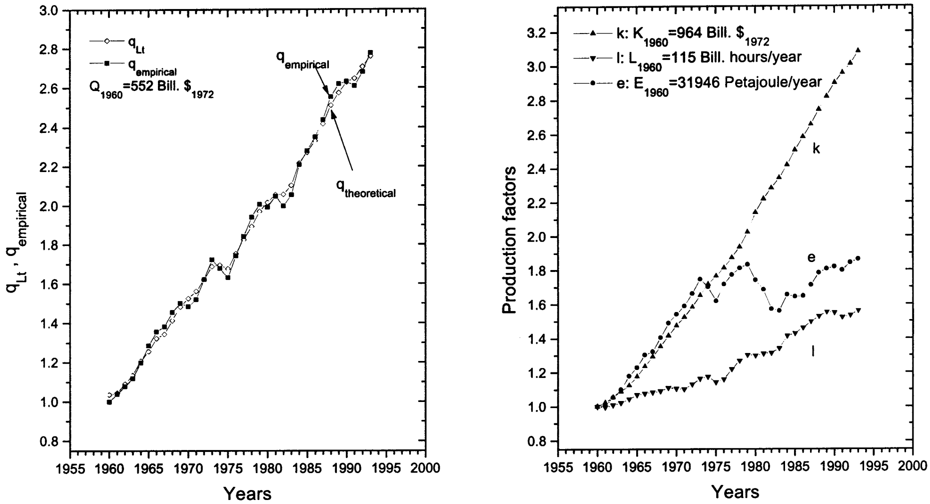

Fig. 1. Theoretical (diamonds) and empirical (squares) growth of annual industrial production $q=Q/Q_{1960}$ (left), and empirical time series of the normalized factors capital $k=K/K_{1960}$, labor $l=L/L_{1960}$ and energy $e=E/E_{1960}$ (right) in 'USA, Industries'.

[6] Factor-independent elasticities of production (EP) α_0, β_0 and $\gamma_0=1-\alpha_0-\beta_0$ are the trivial solutions of the differential equations of which the LINEX elasticities of production are simple non-trivial solutions. Integrating Eq. (2) with these constants for α, β and γ, and with $\delta=0$, results in the energy-dependent Cobb–Douglas function $q_{\text{CDE}}=q_0 k^{\alpha_0} l^{\beta_0} e^{1-\alpha_0-\beta_0}$. Lindenberger (2000) has fitted q_{CDE} to the same time series of output as q_{Lt}, with one change of α_0 and β_0 between 1977 and 1978. He obtained rather good agreement between the theoretical and the empirical data also in this case, and the averages of α_0, β_0 and γ_0 differ only a little from the $\bar{\alpha}$, $\bar{\beta}$ and $\bar{\gamma}$ (and from the elasticities $\bar{\alpha}_R$, $\bar{\beta}_R$, $\bar{\gamma}_R$ computed below). Thus, Eq. (2) with constant EP can be considered as the time average of the growth equation with variable EP. Conceptually, the LINEX production function is preferable to the Cobb–Douglas function, because the latter allows for the thermodynamically impossible (asymptotically) complete substitution of energy by capital, whereas the former does not, thanks to the limitation of factor space to the section where the factor-dependent EP in Eqs. (4) and (5) are non-negative. Therefore, on past growth-paths in factor space, which, of course, did not violate the physical limits to substitution, energy-dependent Cobb–Douglas functions can be good approximations of LINEX and other production functions with variable elasticities of productions. For scenarios of the future, however, the latter should be used.

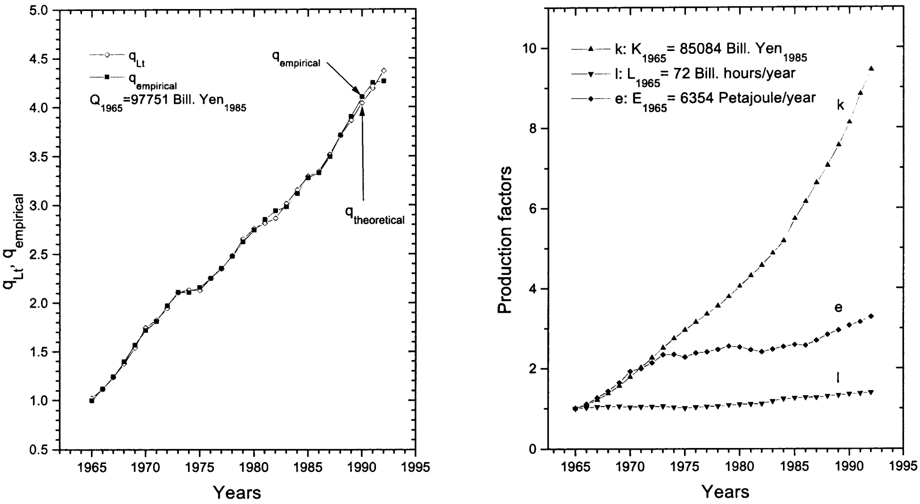

Fig. 2. Theoretical (diamonds) and empirical (squares) growth of annual industrial production $q = Q/Q_{1965}$ (left), and empirical time series of the normalized factors capital $k = K/K_{1965}$, labor $l = L/L_{1965}$ and energy $e = E/E_{1965}$ (right) in 'Japan, Industries'.

The parameter changes allowed between 1977 and 1978 consist in a jump of a to a higher and of c to a lower value in each of the three systems. This implies modeling creativity as a 1-year-pulse. Of course, such a sudden change is only a crude approximation of the steady technological improvements that enhance capital

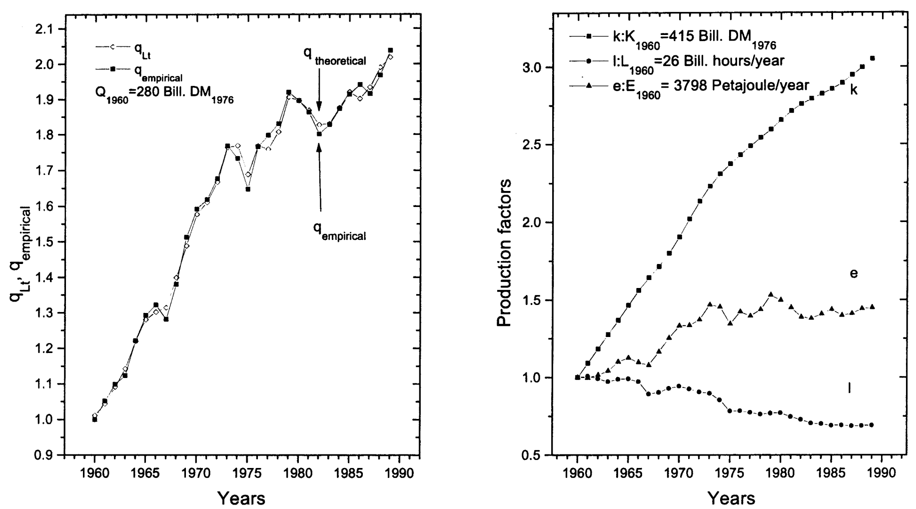

Fig. 3. Theoretical (diamonds) and empirical (squares) growth of annual industrial production $q = Q/Q_{1960}$ (left), and empirical time series of the normalized factors capital $k = K/K_{1960}$, labor $l = L/L_{1960}$ and energy $e = E/E_{1960}$ (right) in 'Germany, Warenproduzierendes Gewerbe'.

efficiency and reduce energy demand. Therefore, in the following we try to describe these steady improvements more realistically, replacing the 1-year-pulse model of creativity by a model of innovation diffusion.

The step functions for the capital-efficiency and energy-demand parameters in the 1-year-pulse model are the limiting cases of smoothly increasing and decreasing functions of the logistics type. Furthermore, experience shows that logistics are typical for growth in complex systems and processes of innovation diffusion (Vester, 1974; Mende and Albrecht, 1990; Danielmeyer and Martinetz, 1996). Thus, mathematical logic and empirical evidence are the motivation for requiring that the technology parameters $a(t)$ and $c(t)$ satisfy the logistics differential equation. For $a(t)$ this equation reads

$$\frac{\mathrm{d}}{\mathrm{d}t}(a(t)-a_2)=a_3(a(t)-a_2)\left(1-\frac{a(t)-a_2}{a_1-a_2}\right), \tag{7}$$

and in the equation for $c(t)$ one has the characteristic coefficients c_i, instead of a_i. The solutions for increasing $a(t)$ and decreasing $c(t)$ are,

$$a(t)=\frac{a_1-a_2}{1+\exp[-a_3(t-a_4)]}+a_2, \quad a_1>a_2, \tag{8}$$

$$c(t)=\frac{c_1-c_2}{1+\exp[-c_3(t-c_4)]}+c_2, \quad c_1<c_2. \tag{9}$$

The positive characteristic coefficients of the logistics, $a_1, \ldots, a_4, c_1, \ldots, c_4$, are determine by minimizing the sum

$$\sum_{i=1}^{T}[q_{\mathrm{empirical}}(t_i)-q_{\mathrm{Lt}}(t_i)]^2, \tag{10}$$

subject to the constraints that α, β and γ are non-negative; t_i are the years of the observation time T, $i=1, \ldots, T$. The appropriate starting values for the characteristic coefficients have been crucial for the non-linear Levenberg–Marquardt minimization procedure. They were computed by a self-consistent iteration scheme (Henn, 2000).

We find that in all countries the energy-demand parameter of the capital stock, $c(t)$, decreases significantly after the first oil-price explosion while $a(t)$ increases somewhat. (This and more econometric details are shown in the Internet Supplement.) These smooth time changes of the capital-related technology parameters reflect structural changes towards less energy intensive production and the technological change towards more efficient combinations of capital, labor and energy, noted by many empirical studies in conjunction with the energy crisis. For example, a recent analysis for Japan by Watanabe (1999) shows that the annual reduction rate of carbon-dioxide emissions because of energy-efficiency improvements increases and decreases between 1970 and 1994 in a way which very much resembles the increasing and decreasing rate of reduction of the energy-demand parameter $c(t)$ of Japan; and the Japanese trend in technology knowledge stock of energy research and development follows a logistics similar to that of the Japanese capital-efficiency parameter $a(t)$. For Germany $c(t)$ does not level off at the end of the eighties, as it does for the USA and Japan. This is consistent with the incentives given to improvements of energy efficiency since the energy crises in Germany.

Of course, the smooth time changes of $a(t)$ and $c(t)$ model only the direct scientific-technological effects of creativity on the production of material goods and services. Nothing can be said about creativity's actions in other fields of human endeavor. Furthermore, one might expect more insights in creativity's working by time series on patents or innovation data. However, there is the problem of the retardation time between the publication of inventions and their sensible economic impacts. An example, now famous because of the award of the Nobel Prize in Physics in the year 2000 to Herbert Kroemer, is the conception of the Wide-Gap Emitter for Transistors in 1957 and the Proposal of Heterojunction Injection Lasers in 1963. Both innovations have revolutionized information technology. But it lasted about 30 years until their economic impact became so evident that the Swedish Academy acknowledged it with the highest scientific honor. Another example are the inventions of the last decades in the field of the rational use of energy and the use of renewable energies. They provide a rich basket of hardware and software that can minimize energy consumption, emissions and costs in complex energy systems at unchanged energy services. However, at the present low prices of the fossil fuels these sophisticated technologies cannot successfully compete in the market with the conventional combustion of coal, oil and gas (see Lindenberger et al., 2000). Only twice, the market penetration of the most cost-effective technologies was helped—by the oil-price explosions. It would be most interesting to collect a representative set of data on the birth of innovations in the minds of creative people and the times when their economic impact is generally noted. But such an empirical study is beyond the scope of our present analysis.

Inserting the computed $a(t)$ and $c(t)$ and the empirical data of k, l, e into the LINEX production function q_{Lt} of Eq. (6) results in the growth curves shown in Figs. 1–3. These curves are somewhat closer to the empirical data than those obtained with creativity as a 1-year-pulse. The biggest improvement is obtained for 'USA, Industries'. In addition we have also computed the growth of gross domestic product (GDP) in the total economies of the USA and Germany with new data from empirical time series ranging from 1960 to 1996 for the USA and from 1960 to 1989 for (the old Federal Republic of) Germany. These results are shown in Fig. 4. In all the systems considered the overall growth of output is similar to the overall growth of gross fixed capital, and the ups and downs of outputs and energy inputs occur at the same times. Labor rises in the USA, stays nearly constant in Japan, and decreases in Germany; its apparently low relative importance is confirmed by the following elasticities of production.

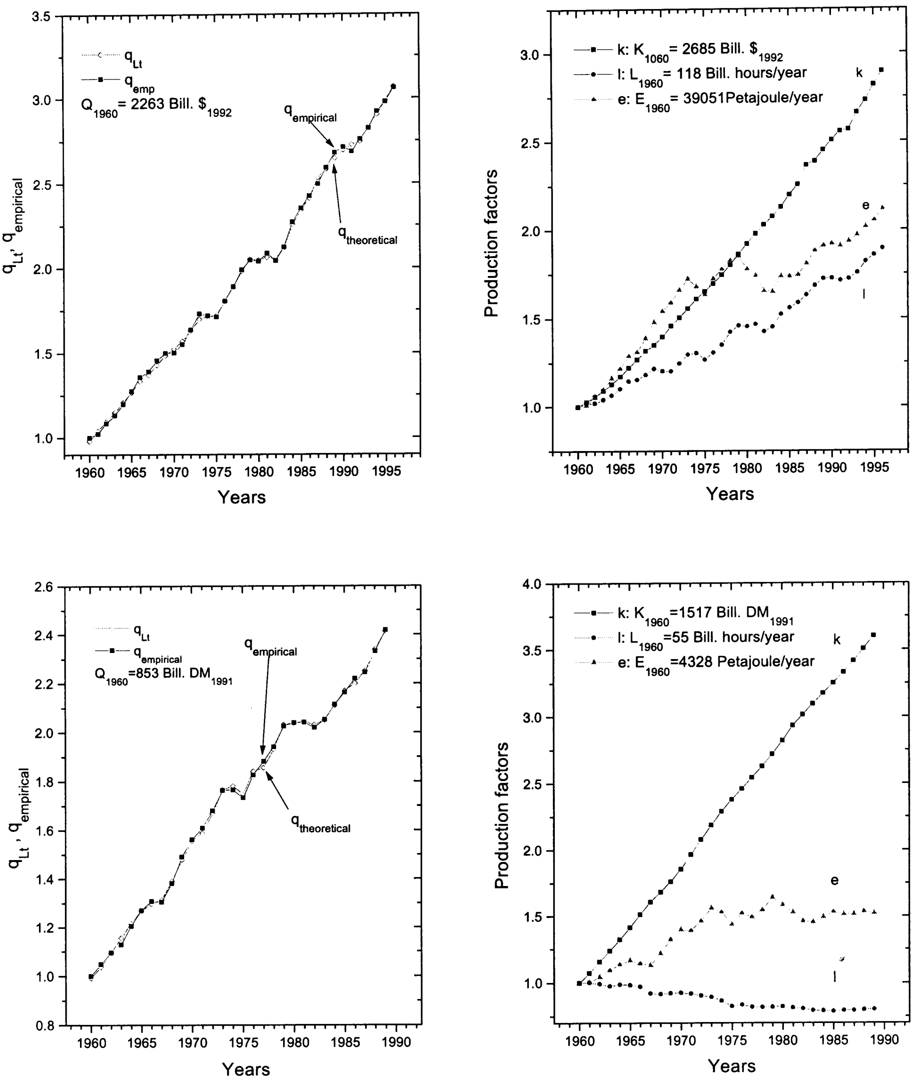

Fig. 4. Theoretical (diamonds) and empirical (squares) growth of annual gross domestic product $q = Q/Q_{1960}$ (left), and empirical time series of the normalized factors capital $k = K/K_{1960}$, labor $l = L/L_{1960}$ and energy $e = E/E_{1960}$ (right) in 'USA, Total Economy' (top) and 'Germany; Total Economy' (bottom).

Observing that $\alpha + \beta + \gamma = 1$ we define renormalized elasticities of production (EP) α_R, β_R, γ_R, δ_R by dividing the original ones by $1 + \delta$. Thus, the sum of the renormalized EP of capital, labor, energy, and creativity is unity. The time-averaged renormalized EP, i.e. the productive powers of capital, $\bar{\alpha}_R$, labor $\bar{\beta}_R$, energy $\bar{\gamma}_R$, and creativity $\bar{\delta}_R$, their standard errors,[7] and the statistical quality measures 'coefficient of determination R^2 and 'Durbin–Watson coefficient d_w' (whose best values are 1 and 2, respectively) are for the considered systems and time intervals:

USA, *Industries*, 1960–1993, $R^2 = 0.997$, $d_w = 0.95$:

$$\bar{\alpha}_R = 0.36(\pm 0.01),\ \bar{\beta}_R = 0.07(\pm 0.01),\ \bar{\gamma}_R = 0.51(\pm 0.02),\ \bar{\delta}_R = 0.06(\pm 0.03).$$

Japan, *Industries*, 1965–1992, $R^2 = 0.998$, $d_w = 1.58$:

$$\bar{\alpha}_R = 0.19 \pm 0.08,\ \bar{\beta}_R = 0.12 \pm 0.09,\ \bar{\gamma}_R = 0.61 \pm 0.15,\ \bar{\delta}_R = 0.08 \pm 0.17.$$

Germany, *Warenproduzierendes Gewerbe*, 1960–1989, $R^2 = 0.994$, $d_w = 1.63$:

$$\bar{\alpha}_R = 0.30 \pm 0.10,\ \bar{\beta}_R = 0.04 \pm 0.10,\ \bar{\gamma}_R = 0.64 \pm 0.15,\ \bar{\delta}_R = 0.02 \pm 0.45.$$

USA, *Total Economy*, 1960–1996, $R^2 = 0.999$, $d_w = 1.91$:

$$\bar{\alpha}_R = 0.46 \pm (0.07),\ \bar{\beta}_R = 0.14 \pm (0.12),\ \bar{\gamma}_R = 0.30 \pm (0.1),\ \bar{\delta}_R = 0.10 \pm (0.08).$$

Germany, *Total Economy*, 1960–1989, $R^2 = 0.999$, $d_w = 1.67$:

$$\bar{\alpha}_R = 0.36 \pm 0.03,\ \bar{\beta}_R = 0.09 \pm 0.02,\ \bar{\gamma}_R = 0.44 \pm 0.04,\ \bar{\delta}_R = 0.11 \pm 0.12.$$

A comparison of the time-averaged elasticities of production, computed with the 1-year-pulse model of creativity, on the one hand, and the innovation-diffusion model, on the other hand, for the industrial sectors of the three countries shows that they do not differ significantly. This is especially true for $\bar{\gamma}$ and $\bar{\gamma}_R$ and confirms the high productive power of energy. Comparably high EP of energy have been obtained by Beaudreau (1998), Ayres and Warr (2002). As is to be expected, in the total economies, with all the service sectors included, the productive powers of labor and creativity turn out to be somewhat larger and those of energy somewhat smaller than in the industrial sectors. Except for capital the time-averaged EP deviate significantly from the factor-cost shares, which are roughly 0.25 for capital, 0.70 for labor, and 0.05 for energy.

[7] The errors in the time-averaged renormalized EP for Japan and Germany have been computed from the time averages of the standard errors of the factor-dependent EP. The latter, in turn, have been computed from the standard errors in the simultaneous Levenberg–Marquardt estimations of all characteristic coefficients according to the method of error propagation. They represent the upper limits of the possible errors, because the method of error propagation treats $a(t)$ and $c(t)$ as independent parameters, whereas increasing a and decreasing c seem to be coupled in the USA and Japan. The error of δ is biggest, because it contains the largest number of contributions (Henn, 2000). The errors in the renormalized EP of the USA are written in parentheses, because in the case of 'USA, Industries', not all the characteristic coefficients were estimated simultaneously, but rather groupwise, and in the case of 'USA, Total Economy', the error margins are obtained from a simultaneous estimation of the coefficients $a_1, \ldots, c_4$ based on the time-series between the years 1965 and 1996. In addition, in this one case, q_0 was allowed to change in time from 0.98 in 1960 to 1.12 in 1973. This eliminated a small discrepancy during the years 1960–1964 between the empirical data and the LINEX function q_{Lt} with the coefficients $a_1, \ldots, c_4$ from the 1965 to 1996 estimation. The difficulties with the estimations for the USA, because there k, l and e are rather close to each other between 1960 and 1965, have been analyzed by Henn (2000) and are discussed in the Internet Supplement. If one excluded the first 5 years from the time-series analysis for the USA, the errors in the parentheses should be close to the maximum errors.

One is tempted to speculate that in the past the big share of cheap energy in the production of wealth has essentially been given to the general population according to the distribution scheme: roughly 30% of GDP to the capital owners and 60–70% to the employees. Ayres (2001) has proposed that correcting for the omission of intermediates in the traditional theory by introducing a two-sector (or multi-sector) production process, where the output of the primary sector is produced by capital, labor and exergy and serves as an input besides capital and labor to the secondary sector(s), can multiply the impact of the exergy inputs and account for the discrepancy between the high productive power and the small cost share of energy. On the other hand, sectorally more disaggregated analyses reveal that the mismatch of elasticities of production and cost shares is typical also for non-primary industries (Lindenberger et al., 2001). Thus, the economy does in fact evolve in disequilibrium characterized by a permanent incentive to increase automation, i.e. to substitute increasingly information-processing, energy-driven capital for expensive labor.

5. Summary and discussion

Economic growth in the USA, Japan and Germany during the last three decades, including the downturns and upswings of the energy crises, is well reproduced by LINEX production functions. Thereby the residual 'technological progress' of neoclassical theory reveals its two principal elements. The first one is the activation of the growing, more and more automated capital stock by energy; and, of course, the people who handle the capital stock have to be qualified appropriately. The second one consists of improvements of organizational and energetic efficiencies of the capital stock by creativity. The short-term impact of the first element is much bigger than that of the second element, but the reverse may be true for the long-term impact, if efficiency improvements fundamentally change the course of economic evolution.

The key to unveiling the elements of technical progress has been a novel method of calculating the elasticities of production of capital, labor and energy. They are determined by differential equations, technological considerations and non-linear optimization. They contain capital-efficiency parameters $a(t)$, logistically increasing with time t, and energy-demand parameters $c(t)$, decreasing with time. These changes in time model the working of creativity via innovation diffusion. The time-averaged elasticities of production, which measure the productive powers of the factors, are for capital close to capital's cost share, for labor and creativity much smaller than labor's cost share, and for energy up to an order of magnitude larger than energy's share in total factor cost. This confirms earlier findings with a 1-year-pulse model for creativity, which also reproduces growth reasonably well, with the three technology parameters staying constant for about 15 years. The basic result of mismatching elasticities of production and cost shares is independent of the special functional form of the chosen production function: Lindenberger (2000) has confirmed this result with other, more complicated LINEX functions and with the simple, energy-dependent Cobb–Douglas function.

Thus, the fundamental equilibrium assumption of neoclassical economics apparently has not been satisfied under the conditions of industrial production reigning during the last three decades in the USA, Japan, and Germany. The economies have been working in boundary cost minima in factor space, where the boundaries, at a given point in time, are established by the state of technology in information processing and automation and prevent the economies from sliding at once into the absolute cost minimum at nearly vanishing labor input. It is to be expected that, with progress in micro- and nano-structuring of transistors, automation will continue to increase and replace expensive labor/capital combinations by cheap energy/capital combinations—as long as the productive powers and cost shares of labor and energy remain in disequilibrium.

The KLEC model is based on the exogeneously given physical inputs of capital, labor and energy. Lindenberger (2000) has added the optimization model PRISE of price induced sectoral evolution with standard behavioral assumptions like profit and utility maximization. This model provides the framework for calculating the inputs of capital, labor and energy as functions of their prices. After a first positive test for Germany it can now be used to look into problems like the effects of energy taxes on sectoral growth and structural change, taking into account potentially sector-specific schemes of recycling the energy taxes in order to lower capital cost and, much more important, labor cost so that the production system may be driven closer towards equilibrium. In equilibrium, with matching factor cost shares and elasticities for capital, labor, and energy, both economic and social stability, as well as the diffusion of energy-saving technology into the market, will be favored much more than it is the case today. In order to get the factor prices before energy taxes, one may try to couple PRISE to input–output analyses, like the ones of Kurz and Salvadori (2000), that yield the dynamics of wage and profit rates, commodity prices and the royalties paid to the owners of exhaustible resources.

Ideally, one may also wish to couple our model of production and growth to a model of consumer and entrepeneurial behavior that is more explicit and detailed than the one used in PRISE, and that includes a theory of shock reactions to energy-price explosions. However, social science models on human behavior sometimes apply, and sometimes they do not, depending upon which modeled subset of the infinite set of human behavioral patterns is matched by the actual group of people to which the model is applied. Empirical studies frequently have shown that the behavior of real people in experimental or laboratory situations was quite different from the assumptions of a given (neoclassical) model (Schoemaker, 1982; Smith, 1989). Therefore, the coupling to a behavioral model beyond the standard one is left to future research. The KLEC model, as it stands, may be considered as an offer to users of KLE-based macroeconomic models (Capros et al., 1989; Yasukawa et al., 1993; Messner and Schrattenholzer, 2000), to use it in the production-function module.

An extension of the KLEC model is required for analyses of future scenarios with environmental and resource constraints. As a simple way of formally taking into account such constraints it has been suggested to multiply the α, β and γ in Eq. (2) by pollution and recycling functions involving entropy production and critical recycling frequencies (Kümmel, 1980, 1998); these functions decrease from unity to zero if pollution increases and materials become scarce. A direct econometric analysis of an economy with pollution may be possible once environmental accounting (Tjahjadi et al., 1999) will have established complete data bases which exhibit the factors and outputs that belong to the traditional basket of goods and services, on the one hand, and those that are dedicated to fighting pollution, on the other hand. This requires very detailed analyses of material and energy flows (Ayres and Simonis, 1994). And probably one will also need a consensus in society on what is to be considered as environmentally unacceptable. The problems of how to reach such a consensus in democratic societies and establish the laws and sanctions that may be neccessary to keep their economies on paths of sustainable development have been discussed by Faber et al. (1995). Contemplating entropy production not only under the aspect of thermodynamic constraints on economic growth but also as a driving force for the formation of dissipative structures, and combining nature's laws and principles of self-organization with the modeling of the growth of human knowledge and innovations is a goal of evolutionary economics (Witt, 1997). Interactions between economists and natural scientist will help pave the road towards that goal. The 'Wilhelm and Else Heraeus-Stiftung' recently offered an opportunity for such interactions by its 243th Seminar "Economic Growth-Driving Forces and Constraints in the Perspective of Economics and the Sciences". The present paper has benefitted from discussions during this seminar and its preparation.

The international, interdisciplinary discourse on energy and entropy in economy and ecology began after the first energy crisis, the discussions on the limits to growth and Georgescu-Roegen (1971) statements on entropy. It should be reactivated with new vigor. Its results may help lawmakers to establish economic boundary conditions that support the market penetration of energy-conserving and non-fossil-energy technologies and distribute energy-derived wealth in the industrial and developing countries in such a way that ecological and social stability can be preserved.

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