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Abstract

From an engineering perspective, a capital good's service is energy conversion – e.g., the physical 'work' done by a machine – and can thus be measured directly by the energy consumed in production. We show important empirical advantages of our concept over traditional measures. The empirical application reveals that our concept avoids a number of conceptual problems of the latter. Furthermore, our measure is more sensitive to fluctuations in economic activity and therefore captures the utilization of the capital stock better. In a growth accounting exercise, this results in higher TFP growth rates, especially in times of global recession.

Keywords: capital service, utilization, energy consumption, total factor productivity, growth accounting
JEL: E22, D24, O47.

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1 Introduction

The search for a proper measure of capital input has a long history, stretching back to the Cambridge Controversy of the 1950s (e.g., Robinson, 1954, and Solow, 1956). The key problems in the measurement of capital services arise in the application of theory to empirical research. The first challenge is to find a procedure for constructing a capital measure that aggregates heterogeneous capital goods into a single index and that still remains consistent with theory. The second challenge is to derive the capital service flow from the capital goods stock. In theory, the relation between capital service flow and the capital goods stock is assumed to be constant.

Given the wide range of economic issues that require proper measurement of capital – for instance, the determinants of economic growth – a broad literature has emerged proposing theoretically consistent solutions to the aforementioned challenges. From an empirical perspective, the measurement of capital services is a demanding task. In contrast to labor, capital services are not purchased by the producer on the market because the producer is usually the owner of the capital goods. Thus, rental prices and quantities of capital services cannot be observed directly. In a seminal paper on the subject, Jorgenson (1963) showed that the rental price for capital can be derived from the price of capital goods using the rate on return on capital and the depreciation rate. In Griliches and Jorgenson (1966) and Jorgenson and Griliches (1967), this approach was used to calculate the total capital service used in production. In both of those papers, the same approach was used as for labor input: rental price was multiplied by the quantity, i.e., the capital stock, while assuming that the relation between capital services and capital stock is constant.

This basic approach became the cornerstone of a large body of literature extending and refining the procedure for measuring capital input – Christensen and Jorgenson (1969, 1970), Inklaar (2010), Hulten (1990), and Diewert (2003), to mention only a few. The approach also found its way into the daily work of statistical institutions. The U.S. Bureau of Labor Statistics (BEL) (Harper, 1999) and the KLEMS project (O'Mahony and Timmer, 2009), for instance, use this approach to construct capital input time series.

However, the implementation of the procedure requires detailed information on the prices of the investment goods, the returns on capital, and the depreciation rate. Furthermore, an even more challenging issue is how to obtain the quantity of capital services. As the relation between the capital stock and the quantity of capital services provided depends on the utilization rate and the work intensity of the capital goods, it is quite difficult to determine. Although authors such as Solow (1957) and Jorgenson and Griliches (1967) have provided some ideas on how to control for the utilization of the capital stock, it has become standard procedure to assume a constant relation between capital stock and capital services (e.g., O'Mahony and Timmer, 2009, on the KLEMS data construction). The construction of the capital stock itself also raises a number of issues that have been generally neglected in the literature. The usual construction of physical capital stock by the perpetual inventory method (PIM) creates several severe empirical problems because a number of essential assumptions that have to be made strongly influence the development of the constructed time series. In particular, the assumptions on the initial capital stock and on the depreciation of capital have a determining influence.

To circumvent these problems, Moody (1974), Costello (1993), and Burnside et al. (1995, 1996) proposed the use of electrical power as an approximation of capital services. Based on the approach of Griliches and Jorgenson (1966), they assumed a direct relation between the electricity consumed and capital services of the total capital stock. However, Jorgenson and Griliches (1967) used the relation between electricity consumed by electric motors and the maximum electricity consumption of installed electric motors (24 hours times 365 days at highest intensity) to calculate the utilization rate of the capital stock, and thus assumed only that the utilization of electric motors and other capital goods is equal. The previously mentioned authors, on the other hand, assumed that the energy efficiency of the electric motors and other capital goods is equal and that using the growth rate of consumed electricity would also capture the increase in capital services of other capital goods.[1]

However, as the efficiency of electric motors is rather high in comparison to other

[1] Costello (1993) and Burnside et al. (1996) assumed a constant relation between electricity consumption and capital services, which implies that there is no increase in energy efficiency. Moody (1974) and Burnside et al. (1995), on the other hand, assumed a constant increase in energy efficiency.

machines such as combustion engines, computers, and air conditioning, this assumption is questionable.[2] Furthermore, on a country level, this assumption might lead to biased results, as the service sector – in particular the transport business – and the primary sector use significant amounts of other energy sources to operate their capital goods. Finally, substitution effects in favor of electricity consumption are mistakenly interpreted as an increase in capital services.

This is the starting point for our paper: inspired by the literature on engineering production functions (e.g., Chenery, 1949), we take an engineering perspective on the problem of measuring capital services and define capital services in terms of the concept of work in physics. Pursuing this idea, we are able to formally derive the relation between capital services and the total energy consumed in production. We allow for variations in energy efficiency by introducing energy efficiency as a function of technological progress. Furthermore, by ascribing the 'work' – defined in accordance with the physics concept – carried out in production to the capital goods used, we show that this concept can easily be included in standard growth models. Finally, by using total energy consumed instead of electrical energy consumed as an approximation of capital services, we resolve the limitation to electrical machines and avoid a corresponding bias.

To empirically evaluate the new concept, we start by comparing time series for capital services based on the new approach to those for the traditional capital stock measure calculated by PIM, the KLEMS data, and the capital service measure based on electricity consumption only. It turns out that the growth rates based on our measure are significantly lower than those provided by the three traditional measures. The reason for the difference in growth rates can be traced back to a higher sensitivity of our measure to economic fluctuations.

In a second step, we perform a growth accounting exercise to determine how the different approaches alter the TFP calculations. As suggested by our comparison of the different time series for capital services, we find that TFP calculations based on our measure lead to significantly higher TFP growth rates than calculations based on

[2]For example, the energy efficiency of electric motors is now at about 90%, as it was in the 1960s, e.g., Griliches and Jorgenson (1967), while for diesel engines, energy efficiency is currently at just 50%.

the traditional capital service measures. Furthermore, it turns out that the number of years with technological regress is significantly reduced.

The paper is organized as follows. The next section introduces our new approach. Section 3 discusses the advantages of our approach for empirical research. In Section 4, the approach is applied to the data and compared to the traditional measures of capital services. Section 5 concludes.

2 Measuring capital services by energy consumption: Theoretical considerations

Ideally, a measure of capital services should possess two characteristics. First, it should be a flow variable because services are absorbed in the production process. Second, it should be a (physical) quantity, not a value or price. From an engineering perspective, capital services can be seen as the transformation of energy into 'work' – as defined in physics – a machine provides in the production process. For example, a machine provides a service by drilling, milling, and cutting, thus providing 'work' in the physics sense. Similarly, streets only provide capital services if used by vehicles, while the motors of vehicles again provide 'work'. Buildings can be used for production only if they are lighted and heated or cooled. In this case, energy is transformed into light, heat, or air conditioning. Even in the special case of the computer, which does not provide physical or mechanical work, energy is transformed to provide data processing.[3] Furthermore, if the capital good is not used, no energy is transformed; that is, no 'work' is provided and thus the capital service is zero. Thus, the 'work' provided by or with the help of the capital good (e.g., streets) is actually the capital service.

However, the energy input is transformed into useful energy output – in our case work – and wasted energy output. The relation between the energy input and the provided 'work' of the capital good depends on the energy conversion efficiency (ECE) of the devices employed and thus on the technological level A implemented. Thus, the relation between useful energy output, e.g., 'work' W – the capital services

[3] Data processing can be interpreted as sequencing work.

– and energy input E can be stated as:[4]

$$W = A\ E. \tag{1}$$

A corresponding CD production function, with Y being output and H being human capital, is then:

$$Y = (W)^{\alpha} H^{1-\alpha} = (AE)^{\alpha} H^{1-\alpha}. \tag{2}$$

To integrate our concept of capital services into growth theory, we must connect the energy used in production to the capital goods purchased for the task at hand. We therefore have to go one step further. Obviously, E is a function of the number of capital goods and the intensity and duration with which they are used. Thus E can be written as $E = \mu K$, with μ being a time-variant measure of utilization. This brings us back to the conventional formulation of aggregated production functions in growth models:

$$Y = (A\mu K)^{\alpha} H^{1-\alpha}. \tag{3}$$

Such a formulation of the aggregated production function, including a variable utilization of K, can be found in Calvo (1975), Chatterjee (2005), and Rumbos and Auernheimer (2001). In these papers, μ is introduced as another control variable. The individuals in these models have to decide which level of utilization to choose to maximize their utility while taking into account that with an increasing μ, the depreciation of K increases as well.

All these papers conclude that the convergence towards equilibrium is slower – and thus the growth rate of K lower – than in models which assume constant utilization of K. For the following empirical evaluation, these theoretical findings imply that utilization-adapted measures of capital services should be characterized by slower growth rates than those without adaptation. In the growth accounting exercise, this would lead to higher TFP estimates based on the utilization-adapted measures.

[4] The relation between Power P and Work W stems from the definition in physics that $P = \frac{\Delta W}{\Delta t} = \frac{\Delta E}{\Delta t}$. Furthermore, the energy conversion efficiency is defined as $\eta = \frac{P_{out}}{P_{in}}$ and corresponds to the ratio between energy output and input. From the combination of the two relations follows Equation 1. The average growth rate of the energy efficiency (Y/E) over all countries in our sample was 1.1 percent. The growth rates by country are shown in Table 1.

3 Physical capital stock vs. energy use: Empirical considerations

The new approach has some important advantages over the use of physical capital stock in empirical applications. It offers an especially promising alternative means of addressing the well-known fundamental problems in the construction of physical capital stock and potential impacts thereof on empirical results. A first advantage is that energy used in production E is a flow variable and is measured in kilowatt hours (kWh). Thus, E is measured as a homogeneous, physical quantity, which allows a consistent accumulation of the capital services of different capital goods. This avoids the well-known problem of using price-weighted quantities for the accumulation of investments, which was a central aspect of the Cambridge Controversy (Robinson, 1954, and Solow, 1956). Furthermore, the complex and difficult task of finding the right price deflator for converting investments into real units becomes superfluous. A second advantage is that E is a flow variable like output and human capital. This makes formulations of production functions consistent in terms of units (Solow, 1957, and Moody, 1974). Furthermore, it fulfills the first desired characteristic of a measure of capital services, as mentioned above, because the capital services are absorbed in the production process. The fact that E is a flow variable further relieves us of the burden of making far-reaching assumptions about the initial capital stock and depreciation rate. Although these two assumptions have a tremendous impact on the results of empirical studies, this issue has seldom been discussed in the literature.[5] Both assumptions influence the level of the initial capital stock and thus the development of the time series of K. This becomes clear if one recalls that constructing a physical capital stock by the PIM with the well-known capital accumulation equation $\triangle K = I - \delta K$ requires the construction of an initial capital stock K_0. Harberger (1978) showed that K_0 can be derived from the investment in $t+1$. K_0 is then given by:[6]

[5] See Diewert (2003) for a discussion of different depreciation rates.

[6] A derivation can be found in the appendix.

$$K_t = \frac{I_{t+1}}{g_I + \delta} \quad , \tag{4}$$

with g_I being the average growth rate of the investments from $t = 0$ to $t = -\infty$ and δ being the depreciation rate. However, as Equation 4 shows, the assumptions on g_I and δ determine K_0 and therefore also g_K. To examine this more closely, we calculated K for the USA for the period 1949 to 2010.[7] Figure 1 shows the influence of different assumptions about g_I on the extrapolation of the investment flow into the past. Because the first available investment value at time $t = 1$ is fixed, assuming a high growth rate before $t = 1$ leads to a steep slope of the investment flow curve for $t = 0$ to $t = -\infty$. The higher the assumed growth rate is, the steeper the slope.

Figure 1 and 2 about here

This leads to a counter-intuitive effect on the level of K_0. With a high assumed growth rate of I, the absolute investment values are strongly increasing during the period $t = -\infty$ to $t = 0$. Correspondingly, the sum of these investments is quite small. Therefore, the assumption of high growth rates of investments before $t = 0$ results in a small K_0. Figure 2 presents this issue quite clearly. Furthermore, Figure 2 shows that the assumption of a high (low) growth rate of I before $t = 0$, leads to a low (high) K_0 and thus to higher (lower) growth rates for K. As shown in Table 2, the average yearly growth rates of K (geometric mean) differ significantly for miscellaneous growth rates of I.

Table 2: Geometric mean of g_K for the USA, 1949-2010

	$g_I = 0$	$g_I = 0.05$	$g_I = 0.1$	$g_I = 0.15$
g_K	2.9718	3.7288	4.2897	4.7402

Remarks: g_K is the geometric mean in percent, with $\delta = 0.1$.

[7]The data is taken from the data set used in the later empirical evaluation (see the appendix for a detailed description of the data).

The assumptions on δ have similarly far-reaching effects on K. As Figure 3 shows, K_0 differs strongly with the supposed depreciation rate. The higher the assumed δ, the smaller K_0 and vice versa.

Figure 3 and 4 about here

However, as Figure 4 and Table 3 show, the assumed depreciation rate has only a minor effect on the growth rate of K.

Table 3: Geometric mean of g_K for the USA, 1949-2010

	$\delta = 0$	$\delta = 0.05$	$\delta = 0.1$	$\delta = 0.15$
g_K	3.3511	3.4664	3.4788	3.4563

Remarks: g_K is the geometric mean in percent, with $g_I = 0.0297$.

However, for empirical research based on the level of K, the assumptions on the depreciation rate might significantly alter the results.

Finally, taking both assumptions together, the resulting growth rates and the level of K for the USA are strongly determined by the assumptions on g_I and δ. Assuming $g_I = 0$ and $\delta = 0.001$ results in a yearly growth rate of 0.2159% while assuming $g_I = 0.15$ and $\delta = 0.15$ results in a yearly growth rate of 4.4822%.

Thus, the use of the flow variable E instead of a stock variable avoids these problems and leaves the empirical results unbiased. Finally, as mentioned above, E as a flow variable fluctuates with the use of capital goods. The issue of capital utilization therefore does not have to be addressed separately. This fact is an important advantage of the new approach, as it is widely acknowledged in the literature that neglecting the fluctuations in the utilization of capital stock leads to inappropriate measurement of capital services with a corresponding impact on the empirical results (see, e.g., Burnside et al., 1995, 1996, Shapiro, 1993, Hulten, 1986, Berndt and Fuss, 1986, and Basu, 1996). Particularly in times of below-average capital utilization, strong deviations between capital services and the physical capital stock are to be expected.

Solutions have been proposed for all of the aforementioned problems with the construction of the capital stock variable, yet they require substantial efforts to correct for the potential distortions and offer uncertain chances of success (see Hulten, 1990, for a review). Although the advantages of the new approach for empirical studies are obvious, it remains to be tested whether its application leads to significantly different results and whether these deviations are in line with the arguments discussed above. For that purpose, we compare the different capital service time series and conduct a growth accounting exercise.

4 Empirical assessment

To keep the empirical assessment as simple as possible, we start with Equation 2 and assume that human capital is simply given by $H = AL$, with L being labor. This formulation results in the circumstance that all advances in human capital are captured by the TFP measure. Rewriting the production function in growth rates and solving for the growth rate of A, we get the well-known primal growth accounting equation:

$$\frac{\dot{A}}{A} = \frac{\dot{Y}}{Y} - \alpha \frac{\dot{E}}{E} - (1-\alpha)\frac{\dot{L}}{L}. \tag{5}$$

For the empirical application, we approximate Y by real GDP and L by hours worked. For a comparison, we construct K using the PIM, assuming a depreciation rate of 0.1 and a country-specific growth rate for I before $t = 0$.[8] The three time series are taken from the Penn World Table, Version 7.1 (PWT v. 7.1). E was taken from the International Energy Agency (IEA) data on 'total final consumption of end-use sectors' (TFC) measured in kilowatt hours (kWh), which is E. For further comparisons we use the IEAs 'total final *electricity* consumption of end-use sectors' (E_{ELEC}), which is a measure in line with the approach of Moody (1974), Costello (1993), and Burnside et al. (1995, 1996) and the capital service measure in the

[8]These were calculated as the geometric mean of the observed growth rates of the investments for the time period $t > 0$.

KLEMS database (K_{KLEMS}) representing the approach based on Jorgenson and Griliches (1967).[9] For α, the usual share of 1/3 is assumed.[10] Our sample includes 50 countries. The longest time period covered by a country is 1961-2010.

We start our evaluation by calculating the geometric mean of the growth rates of K, E, and E_{ELEC} for the 50 countries in the sample (Table 4). It turns out that in 45 out of the 50 countries analyzed, the growth rate of K was larger than the growth rate of E. Only for Argentina, Greece, Singapore, Trinidad & Tobago, and Venezuela was this not the case. Somewhat surprisingly, the growth rate of E_{ELEC} is larger than that of K and E in 28 countries and larger than E only in another 18 countries. Thus, in 46 countries, electricity consumption grew faster than total energy consumption. However, these different growth rates are due mainly to a substitution effect towards electricity consumption. For example, for the USA, the share of electricity in TFC in 1961 was 7.6% while in 2010 it was 21.8%. Obviously, this increase does not completely represent an increase in capital services, because the use of other energy sources in production has diminished simultaneously. Obviously, the interpretation of the growth rate of electricity consumption as the growth rate of capital services would strongly overstate the development of the capital services. The average growth rate of K over all countries was 3.71%, for E_{ELEC} 3.83% while for E it was 2.15%. The difference in growth rates between K and E is not due to the assumptions used to construct the initial capital stock. Calculating the g_Is and δs that lead to equal growth rates of K and E, we arrive at implausible small parameter values (e.g. USA: no combination with $\delta > 0.01$ and $g_I > -.00129718$ leads to $g_K = g_E$).[11] Thus, the difference in growth rates is not due to the construction of the initial capital stock. Finally, we turn to the capital service measure K_{KLEMS}, which is the product of a rental price multiplied by a capital stock quantity measure constructed by PIM. Comparing its growth rate to those of the measures discussed above, it turns out that $g_{K_{KLEMS}}$ are even higher than those for electricity consumption (see Table 5). Due to the smaller country coverage in the KLEMS database, the sample is reduced

[9] Unfortunately, the data coverage of the KLEMS database is limited and our sample is reduced to 18 countries if the KLEMS measure is used.

[10] A detailed description of the construction of the different variables used in the calculations is provided in the appendix.

[11] The detailed results for all countries are available upon request.

to 18 countries. In 16 out of these 18 countries, the growth rate of K_{KLEMS} is larger than the growth rates of K, E, and E_{ELEC}.

One reason for the remaining positive difference in growth rates of the different measures might be the neglected utilization rate. Obviously, a smaller drop in the growth rates of a measure during recessions would lead to a higher average growth rate. This would also be in line with the theoretical predictions of the growth models described above, which include the utilization rate as an additional control variable. Taking a closer look at the development of the two measures over time, we therefore calculate the yearly average growth rate of K, E, and E_{ELEC} over all countries, thus investigating the cross-sectional dimension. It turns out that in 36 out of 50 years, the yearly average growth rate of K was larger than that of E (see Table 6). The positive deviations were particularly high in years of global recessions (e.g., the oil price shocks of 1973-1975 and 1979-1983, the Asian financial crisis of 1997-1999, the dot-com bubble burst of 2000-2002, and the financial crisis of 2008-2009). Concerning the growth rate of E_{ELEC}, it turns out that it was larger than that of K in 31 years. Furthermore, it was larger than that of E in 47 years and remained positive in 5 out of 6 cases when the growth rate of E was negative. These findings are the result of the above-mentioned substitution effect. Turing to K_{KLEMS} (Table 7), we find that in 34 out of 37 years, the growth rate of K_{KLEMS} was larger than that of K. For E, the growth rate in 35 years was smaller than that of K_{KLEMS}. Even in years in which E indicates decreasing capital services, the growth rate of K_{KLEMS} suggests that the capital services grew by at least 3.39% up to a growth rate of 5.96%.

However, because the yearly average growth rate might confound the analysis since the different countries might follow asynchronous business cycles, we turn to the yearly data per country to investigate the utilization issue in even more detail. We have 1,931 observations, and in 1,208 cases (62.56%), the growth rate of K was larger than that of E. Furthermore, in 71.31% cases the growth rate of E_{ELEC} was bigger as the one of E. Turning to the K_{KLEMS} measure we find that in 81.52% of the 541 observations its growth rate was larger than that of E. In 80.96% of the observations the growth rate of K_{KLEMS} was also larger than that of K.

Finally, even on a yearly basis, the results are blurred because booms and recessions might overlap a years end. Therefore we count how many quarters in a year showed a negative growth rate of real GDP.[12] Obviously, the utilization of the capital stock – and thus of the capital services – fluctuates with the business cycle. Therefore, a proper measure should capture such fluctuations. Figure 5 shows the growth rates of K, E, E_{ELEC} and for comparison L depending on the number of quarters with a negative growth rate of real GDP.

Figure 5 about here

The figure confirms the results of the analysis above. Even in years with four quarters of negative economic growth, the growth rate of K remains positive in 81.25% of the observations, suggesting that the capital services grew even in severe recessions. In contrast, the growth rates of E show a plausible decrease with a rising number of quarters with negative economic growth. In years in which all quarters were characterized by negative economic growth, the growth rate of E is negative in 87.50% of the observations, paralleling the development of L. As the labor measure is a very good indicator for the economic activity in a country, the similar changes in g_L and g_E indicate that E captures changes in the utilization of the capital stock quite well. Finally, repeating the analysis for K_{KLEMS} (see Figure 6), we see that the measure does not capture the fluctuations in economic activity at all.

Figure 6 about here

Concerning calculations of TFP via the growth accounting approach, the implications of these findings are obvious. In all cases in which g_K is larger than g_E, the TFP calculated based on the capital stock measure will tend to be underestimated. Using Equation 5, we calculate an energy-consumption-based TFP (TFP_E) and for comparison, a capital-stock-based TFP (TFP_K). For the latter, we replace $\frac{\dot{E}}{E}$ with

[12] Unfortunately, due to data limitations on quarterly GDP data, our sample is thus reduced to 840 observations.

$\frac{\dot{K}}{K}$ in Equation 5. As expected, for the 45 countries in which K grew faster than E, the TFP_E measure was larger than TFP_K (Table 8). Among these 45 countries, the TFP_E measure is on average 0.6511 percentage points larger than TFP_K with a standard deviation of 0.6582, minimum difference of 0.0004, and maximum difference of 3.2126 percentage points. For the USA, for example, the difference is quite large: the TFP_E is 1.75 while the TFP_K is only 0.91.

Taking a closer look at the development of the two measures over time, we calculated the average growth rate of TFP_E and TFP_K by year over all countries (Table 9). It turns out that the TFP_E measure shows only a single year (2009) of technological regress, which is in line with the findings in Burnside et al. (1996). In particular, in years of global economic contractions (e.g., the oil price shocks of 1973-1975 and 1979-1983, the Asian financial crisis of 1997-1999, the dot-com bubble burst of 2000-2002, and the financial crisis of 2008-2009), the TFP_E measure provides high positive deviations from the traditional TFP_K measure. Obviously, TFP calculations based on K_{KLEMS} and E_{ELEC} lead to even higher deviations from TFP_E.

5 Conclusion

In this paper, we argued that seen from an engineering perspective, capital services are simply the transformation of energy, e.g., by a machine, into 'work' as defined in physics. Capital services can thus be measured directly by the total energy consumed in production. Furthermore, we showed that this concept is compatible with traditional growth models. In addition, we demonstrated that for empirical applications, the approach of approximating capital services by consumed energy has some important advantages over the traditional use of physical capital stock as a measure of capital services: in contrast to the latter, no assumptions on initial capital stock, depreciation, price developments, or capital utilization are required. For an empirical assessment, we compared the three traditional capital service measures to ours. It turns out that our measure produces significantly lower capital service growth rates than the traditional measures. We traced the source of these differences back to a higher sensitivity of our measure to fluctuations in economic activity. Our TFP calculations, based on capital services measured by consumed energy, therefore lead to higher TFP growth rates than comparable calculations based on the traditional capital service measures. These positive deviations proved particularly large in times of worldwide contractions.

Appendix

Derivation of K_0 from investments in period $t+1$. Following Harberger (1978), we assume that investments were growing with a constant growth rate before $t=0$:

$$I_t = (1+g)I_{t-1} = (1+g)^2 I_{t-2} = \ldots = (1+g)^{\infty} I_{t-\infty} \quad . \tag{6}$$

Furthermore we assume a geometric depreciation as common for the PIM:

$$K_t = I_t + (1-\delta)I_{t-1} + (1-\delta)^2 I_{t-2} + \ldots + (1-\delta)^{\infty} I_{t-\infty} \quad . \tag{7}$$

Combining Equations 6 and 7 we arrive at:

$$K_t = I_t + \frac{(1-\delta)}{(1+g)} I_t + \left(\frac{(1-\delta)}{(1+g)}\right)^2 I_t + \ldots + \left(\frac{(1-\delta)}{(1+g)}\right)^{\infty} I_t = I_t \sum_{\tau=0}^{\infty} \left(\frac{(1-\delta)}{(1+g)}\right)^{\tau} . \tag{8}$$

The second term on the right hand side is a geometric series of the form:

$$y = x^0 + x^1 + x^2 + \ldots + x^{\tau} \quad . \tag{9}$$

With $x = \left(\frac{(1-\delta)}{(1+g)}\right)$. Multiplying both sides by x leads to:

$$xy = x^1 + x^2 + x^3 + \ldots + x^{\tau+1} \quad . \tag{10}$$

Subtracting Equation 10 from 9 results in:

$$\begin{aligned} y - xy &= x^0 - x^{\tau+1} \\ \Leftrightarrow (1-x)y &= 1 - x^{\tau+1} \\ \Leftrightarrow y &= \frac{1 - x^{\tau+1}}{(1-x)} \quad . \end{aligned} \tag{11}$$

For $\lim_{\tau\to\infty} x^{\tau+1} = 0$ Equation 11 becomes:

$$y = \frac{1}{(1-x)} = \frac{1}{\left(1 - \frac{(1-\delta)}{(1+g)}\right)} \quad . \tag{12}$$

Introducing Equation 12 into 8 results in:

$$K_t = I_t \sum_{\tau=0}^{\infty} \left(\frac{(1-\delta)}{(1+g)}\right)^{\tau} = I_t \frac{1}{1 - \frac{1-\delta}{1+g}} = \frac{I_{t+1}}{(1+g)} \frac{1}{\left(1 - \frac{1-\delta}{1+g}\right)} = \frac{I_{t+1}}{g+\delta} \tag{13}$$

which is Equation 4.

Data description

The data used for the TFP estimates along with the variable definitions in the empirical application come from two main sources: the Penn World Table, Version 7.1, and the International Energy Agency.[13] Output, Y in USD, is derived from purchasing power parities (PPP) converted GDP per capita (Laspeyres index) at 2005 constant prices times population ($rgdpl2 \times pop \times 1000$). Total hours worked by employees, L, is computed from output Y divided by PPP converted GDP Laspeyres per hour worked by employees at 2005 constant prices ($Y/rgdpl2th$). Data on total final energy consumption by the different end-use sectors in tons of oil equivalent (toe), $TFEC$, comes from the IEA.[14] The data is converted into kilowatt hours (kWh), variable E, according to the conversion of 1 toe = 11,630 kWh. By definition, the energy efficiency variable in USD per kWh is derived from output divided by total final energy consumption by the different end-use sectors in kWh, Y/E. The Perpetual Inventory Method (PIM) with a constant depreciation rate of $\delta = 10\%$ is used as a standard procedure to derive the physical capital stock, according to $K_t = inv_t + (1-0.1) \times K_{t-1}$, where inv_t equals investment in period t. The initial capital

[13]For definitions and sources of the variables used, see Table A1: Data Sources.

[14]Definition of 'total final consumption (TFC)': the sum of consumption by the different end-use sectors. Total final consumption is broken down into energy demand in the following sectors: industry, transport, other (includes agriculture, residential, commercial, and public services) and non-energy uses. Industry includes manufacturing, construction, and mining industries. In final consumption, petrochemical feedstocks appear under industry use.

stock in each country is derived from an assumed constant growth for investment (g_I) and depreciation (δ) over the sample period. Hence, the initial capital stock in each country is derived from $inv_1/(g_I + \delta)$.

Table A1: Data Source.

$rgdpl$	PPP Converted GDP Per Capita (Laspeyres), derived from growth rates of c, g, i, at 2005 constant prices. Source: PWT v. 7.1.
$rgdpl2$	PPP Converted GDP Per Capita (Laspeyres), derived from growth rates of domestic absorption, at 2005 constant prices. Source: PWT v. 7.1.
$rgdpl2th$	PPP Converted GDP Laspeyres per hour worked by employees at 2005 constant prices. Source: PWT v. 7.1.
pop	Population (in 1000). Source: PWT v. 7.1.
ki	Investment Share of PPP Converted GDP Per Capita at 2005 constant prices [$rgdpl$]. Source: PWT v. 7.0.
inv	Total Investment at 2005 constant prices, derived from $ki \times (rgdpl \times pop \times 1000)$.
K_{KLEMS}	Capital service measure CAP_QI, volume indices, 1995 = 100 (here: rebased to the year 2005). Source: EU KLEMS database, November 2009, accompanying data are available at www.euklems.net.

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Table 1: Growth rate of energy efficiency (geometric mean)

Country	Period	Energy efficiency growth rate
ARG	1972 – 2010	0.28
AUS	1961 – 2010	1.19
AUT	1961 – 2010	0.45
BEL	1961 – 2010	0.85
BGR	1990 – 2010	4.26
BRA	1972 – 2010	0.37
CAN	1961 – 2010	1.13
CHE	1961 – 2010	-0.19
CHL	1972 – 2010	0.57
COL	1972 – 2010	1.71
CYP	1988 – 2010	0.68
CZE	1991 – 2010	3.32
DNK	1961 – 2010	0.98
ESP	1961 – 2010	-0.32
EST	1991 – 2010	5.37
FIN	1961 – 2010	0.77
FRA	1961 – 2010	0.83
GBR	1961 – 2010	2.07
GER	1971 – 2010	1.78
GRC	1961 – 2010	-1.10
HKG	1972 – 2010	1.94
HUN	1981 – 2010	1.54
IRL	1961 – 2010	1.32
ISL	1961 – 2010	-0.44
ISR	1996 – 2010	0.80
ITA	1961 – 2010	-0.01
JAM	1987 – 2010	-0.75
JPN	1961 – 2010	0.59
KOR	1972 – 2010	0.06
LTU	1994 – 2010	3.54
LUX	1961 – 2010	2.08
LVA	1994 – 2010	3.51
MEX	1972 – 2010	0.19
MLT	1988 – 2010	2.00
NLD	1961 – 2010	-0.09
NOR	1961 – 2010	0.88
NZL	1961 – 2010	-0.15
PER	1972 – 2010	1.24
POL	1990 – 2010	3.24
PRT	1961 – 2010	-0.39
ROM	1990 – 2010	4.54
SGP	1972 – 2010	-0.92
SVK	1990 – 2010	4.06
SVN	1991 – 2010	1.26
SWE	1961 – 2010	0.92
TTO	1992 – 2010	-2.26
TUR	1961 – 2010	0.24
TWN	1972 – 2010	0.85
USA	1961 – 2010	1.76
VEN	1972 – 2010	-1.54
Average		1.10

Figure 1: U.S. Investments for different g_I ($\delta = 10\%$)

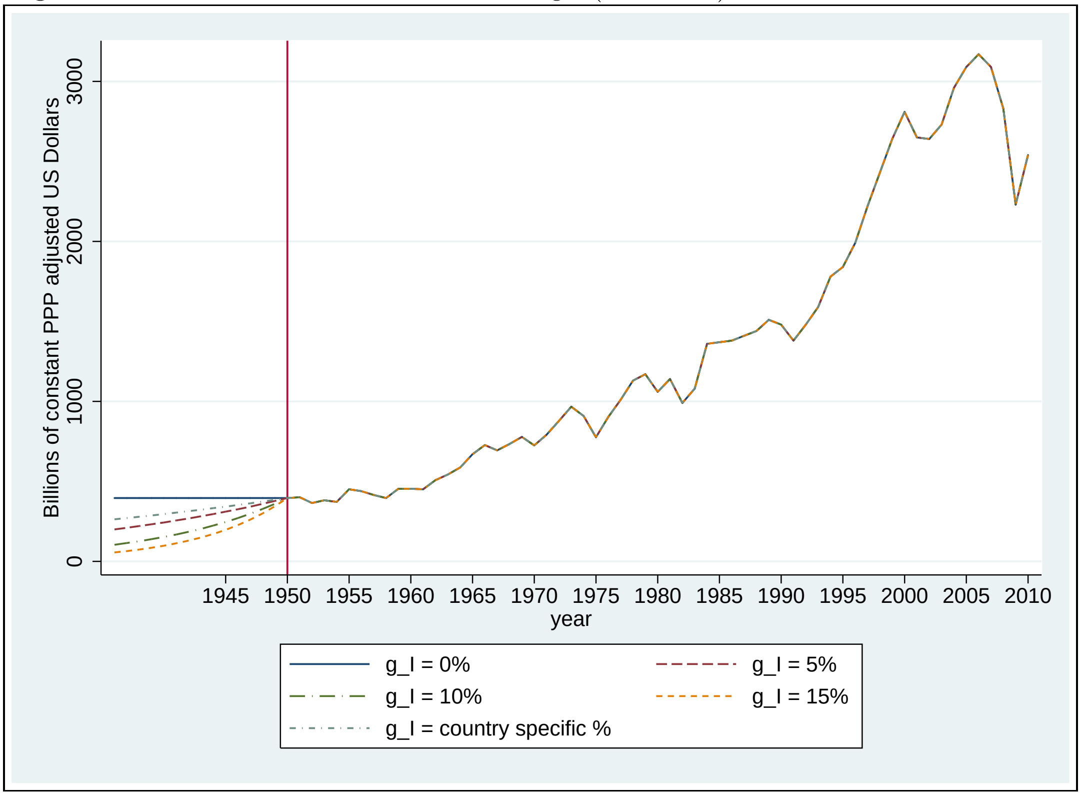


Figure 2: Capital stocks of the USA for different g_I ($\delta = 10\%$)

Figure 3: Capital stocks of the USA for different δ (g_I = country-specific %)

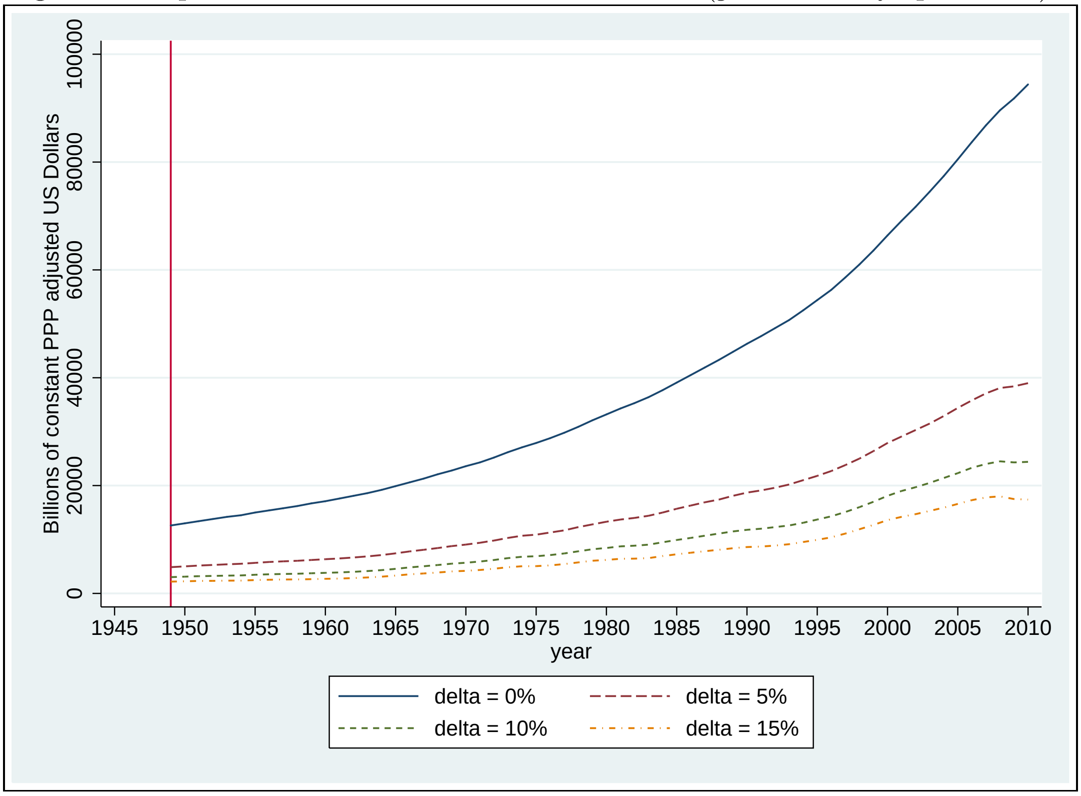


Figure 4: Capital stocks of the USA for different δ in logs (g_I = country-specific %)

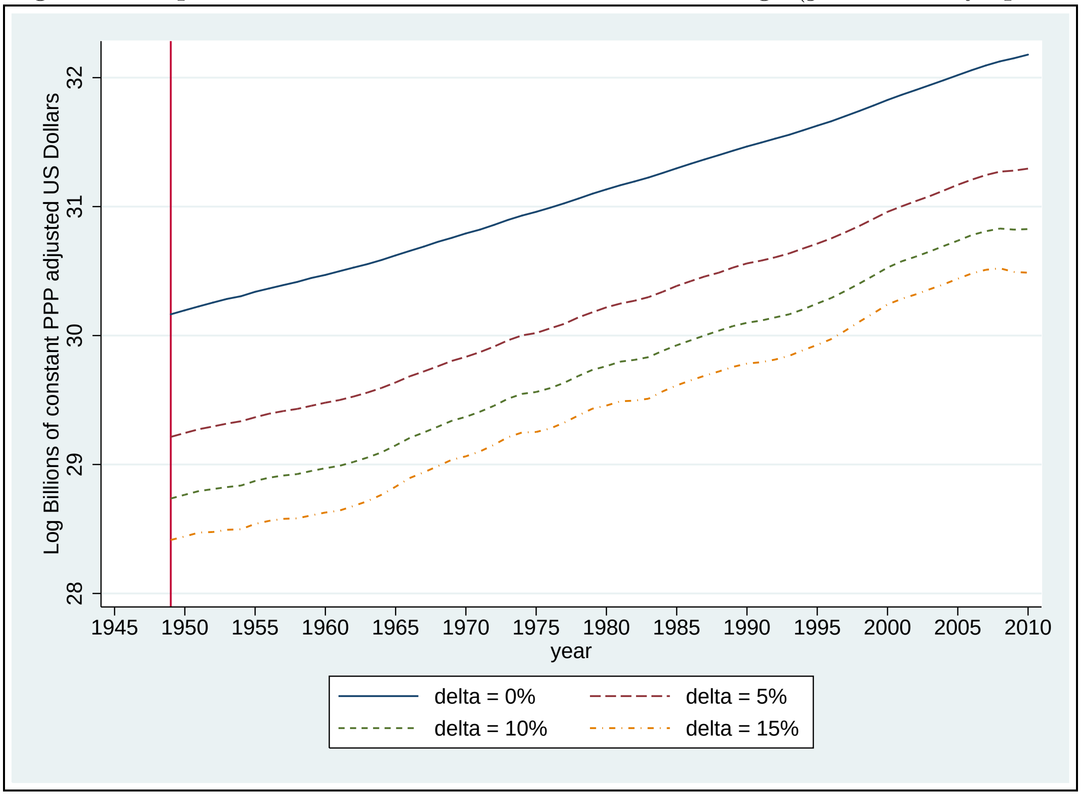


Table 4: Growth rates of E, K and E_{ELEC}

Country	Period	g_K	g_E	$g_K - g_E$	$g_{E_{ELEC}}$
ARG	1972 –2010	2.13	2.18	-0.06	4.34
AUS	1961 –2010	3.37	2.30	1.06	4.82
AUT	1961 –2010	3.62	2.36	1.26	3.32
BEL	1961 –2010	3.10	1.85	1.25	3.97
BGR	1990 –2010	-0.06	-3.06	3.00	-1.25
BRA	1972 –2010	3.74	2.98	0.76	5.87
CAN	1961 –2010	4.04	2.16	1.89	3.17
CHE	1961 –2010	2.61	2.06	0.54	2.53
CHL	1972 –2010	4.08	3.32	0.76	5.24
COL	1972 –2010	4.14	1.77	2.37	4.46
CYP	1988 –2010	3.05	3.04	0.00	5.36
CZE	1991 –2010	2.53	-0.54	3.07	1.27
DNK	1961 –2010	3.63	1.40	2.23	3.72
ESP	1961 –2010	4.91	3.91	0.99	5.82
EST	1991 –2010	2.25	-3.19	5.44	-0.05
FIN	1961 –2010	3.04	2.08	0.96	4.46
FRA	1961 –2010	3.49	1.99	1.50	3.92
GBR	1961 –2010	3.33	0.49	2.84	2.08
GER	1971 –2010	1.18	0.10	1.08	1.69
GRC	1961 –2010	4.47	4.50	-0.03	6.69
HKG	1972 –2010	5.98	3.56	2.42	5.39
HUN	1981 –2010	1.19	-0.54	1.73	0.92
IRL	1961 –2010	4.79	2.72	2.07	5.21
ISL	1961 –2010	3.87	3.56	0.31	7.11
ISR	1996 –2010	3.25	2.52	0.74	3.33
ITA	1961 –2010	3.14	2.67	0.47	3.62
JAM	1987 –2010	2.52	2.29	0.23	3.50
JPN	1961 –2010	5.64	3.28	2.36	4.52
KOR	1972 –2010	9.11	6.43	2.69	10.01
LTU	1994 –2010	9.82	0.39	9.43	1.46
LUX	1961 –2010	3.45	1.68	1.77	3.17
LVA	1994 –2010	9.87	0.23	9.64	2.05
MEX	1972 –2010	3.68	2.90	0.78	5.19
MLT	1988 –2010	2.52	1.41	1.11	2.80
NLD	1961 –2010	3.11	2.96	0.15	4.09
NOR	1961 –2010	3.02	2.38	0.64	2.72
NZL	1961 –2010	2.98	2.59	0.39	3.77
PER	1972 –2010	2.61	1.64	0.97	4.45
POL	1990 –2010	2.94	0.60	2.34	1.00
PRT	1961 –2010	4.73	3.83	0.90	5.75
ROM	1990 –2010	-0.51	-2.83	2.32	-1.29
SGP	1972 –2010	6.60	7.96	-1.36	7.44
SVK	1990 –2010	0.61	-1.52	2.13	0.14
SVN	1991 –2010	5.58	1.65	3.93	1.51
SWE	1961 –2010	2.08	1.22	0.86	2.85
TTO	1992 –2010	1.00	7.85	-6.85	4.62
TUR	1961 –2010	6.01	4.20	1.81	8.96
TWN	1972 –2010	7.71	5.49	2.22	7.00
USA	1961 –2010	3.74	1.22	2.52	3.38
VEN	1972 –2010	2.04	3.65	-1.62	5.35
Average		3.71	2.15	1.56	3.83

Notes: K_0 was constructed by applying a country-specific g_I and a depreciation rate of $\delta = 0.1$.

Table 5: Growth rates of K, K_{KLEMS}, E, and E_{ELEC}

Country	Period	g_K	$g_{K_{KLEMS}}$	g_E	$g_{E_{ELEC}}$
AUS	1971 – 2007	2.78	4.30	2.00	4.12
AUT	1977 – 2007	2.55	2.86	1.56	2.45
BEL	1971 – 2006	2.58	4.08	0.93	3.07
CZE	1996 – 2007	2.75	4.29	-0.13	1.09
DNK	1971 – 2007	3.02	3.47	0.08	2.40
ESP	1971 – 2007	3.86	4.75	3.13	4.74
FIN	1971 – 2007	2.53	4.24	1.37	3.81
FRA	1971 – 2007	2.68	2.98	0.74	3.34
GBR	1971 – 2007	2.91	4.36	0.15	1.34
GER	1971 – 2007	1.21	3.36	0.10	1.82
HUN	1996 – 2007	3.11	2.11	0.48	1.36
IRL	1989 – 2007	5.40	6.93	3.00	4.46
ITA	1971 – 2007	2.67	3.62	1.19	2.90
JPN	1971 – 2006	4.05	4.62	1.54	3.00
NLD	1971 – 2007	2.46	3.41	1.41	2.89
SVN	1996 – 2006	6.39	8.18	1.21	3.01
SWE	1994 – 2007	2.23	4.45	-0.12	0.49
USA	1971 – 2007	3.86	5.09	0.68	2.68
Average		3.17	4.28	1.07	2.72

Notes: K_0 was constructed by applying a country-specific g_I and a depreciation rate of $\delta = 0.1$.

Table 6: Growth rates of K, E and E_{ELEC} by year

Year	g_K	g_E	$g_K - g_E$	$g_{E_{ELEC}}$
1961	6.74	5.06	1.68	8.76
1962	6.15	7.11	-0.97	9.01
1963	6.28	8.11	-1.83	8.46
1964	7.28	5.47	1.81	10.21
1965	7.23	6.42	0.81	8.29
1966	6.92	5.98	0.95	8.49
1967	6.15	4.98	1.16	7.30
1968	5.84	7.29	-1.45	8.60
1969	6.25	7.49	-1.24	10.02
1970	6.48	8.36	-1.88	10.87
1971	5.76	3.42	2.34	7.73
1972	5.85	5.72	0.13	9.44
1973	6.80	7.50	-0.70	9.07
1974	6.83	1.28	5.55	5.47
1975	4.24	-0.48	4.71	2.92
1976	4.52	6.90	-2.37	8.55
1977	4.35	3.49	0.85	6.38
1978	4.01	4.42	-0.42	7.08
1979	4.42	4.22	0.20	7.13
1980	4.40	-0.55	4.95	4.11
1981	3.79	-1.19	4.98	2.53
1982	2.66	-0.63	3.29	2.62
1983	1.62	1.10	0.53	4.72
1984	2.15	3.67	-1.52	6.39
1985	1.86	3.07	-1.21	4.08
1986	2.39	2.44	-0.04	4.27
1987	3.14	3.80	-0.67	6.09
1988	3.80	2.78	1.01	4.91
1989	3.80	2.91	0.89	3.72
1990	3.42	1.87	1.55	3.00
1991	2.41	1.18	1.23	2.30
1992	2.07	-0.71	2.78	3.36
1993	2.02	0.99	1.03	2.30
1994	2.65	2.60	0.05	3.44
1995	3.28	2.84	0.44	4.00
1996	3.45	4.78	-1.33	4.33
1997	4.24	1.51	2.73	3.29
1998	4.36	1.37	2.99	3.17
1999	3.52	1.06	2.46	2.53
2000	3.82	1.67	2.15	4.11
2001	3.17	1.64	1.54	2.46
2002	2.71	0.49	2.23	2.36
2003	2.98	2.93	0.05	3.49
2004	3.80	3.36	0.44	3.16
2005	4.36	1.48	2.88	2.53
2006	4.95	2.28	2.66	3.44
2007	5.49	1.34	4.15	3.18
2008	4.67	0.86	3.82	1.47
2009	1.01	-4.13	5.14	-3.18
2010	1.80	3.74	-1.94	3.42

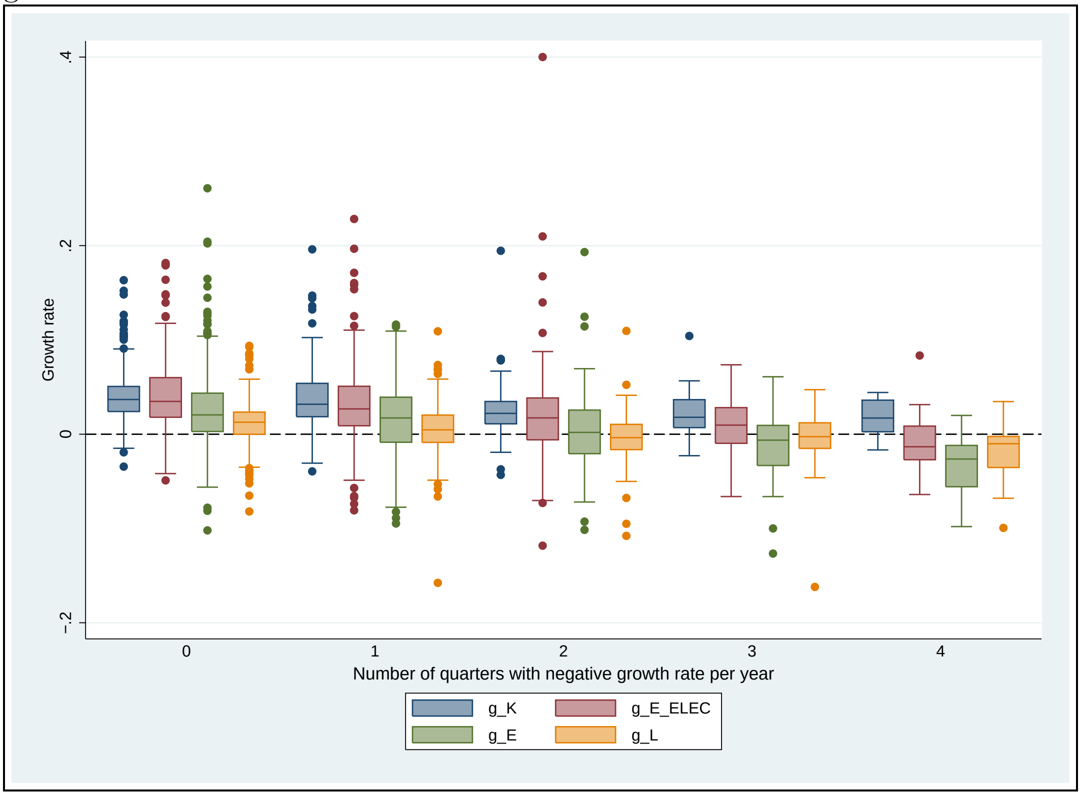
Notes: K_0 was constructed by applying a country-specific g_I and a depreciation rate of $\delta = 0.1$.

Table 7: Growth rates of K, K_{KLEMS}, E, and E_{ELEC}

Year	g_K	$g_{K_{KLEMS}}$	g_E	$g_{E_{ELEC}}$
1971	5.43	7.12	2.61	6.68
1972	5.13	6.39	6.01	8.93
1973	5.94	6.52	6.80	8.52
1974	4.72	5.96	-3.00	3.28
1975	2.53	4.67	-2.44	0.55
1976	3.00	4.59	6.07	7.65
1977	2.89	4.70	0.99	4.06
1978	2.60	4.65	3.43	5.38
1979	3.00	4.86	4.08	5.18
1980	2.77	4.83	-4.17	1.38
1981	1.57	4.09	-3.54	0.95
1982	1.13	3.39	-3.45	0.29
1983	1.14	3.28	0.76	3.00
1984	1.88	3.69	2.80	5.04
1985	2.12	4.08	2.55	4.07
1986	2.46	3.98	2.05	2.72
1987	2.77	4.21	2.05	4.52
1988	3.70	4.61	1.60	4.01
1989	4.03	4.91	1.20	3.80
1990	3.82	4.58	1.27	3.11
1991	2.87	3.73	3.32	3.14
1992	2.36	3.45	-0.41	1.53
1993	1.51	2.57	0.54	1.48
1994	2.01	2.97	1.91	2.82
1995	2.63	3.55	2.10	2.38
1996	2.98	4.20	3.99	3.07
1997	3.46	4.64	-0.02	2.33
1998	4.01	5.48	1.23	2.37
1999	4.04	5.68	0.84	2.17
2000	4.17	5.19	1.53	2.94
2001	3.52	4.45	1.97	2.34
2002	3.04	3.75	-0.42	1.82
2003	3.03	3.30	2.54	1.65
2004	3.35	3.27	1.47	2.27
2005	3.48	3.52	0.79	1.42
2006	3.81	3.66	0.10	2.45
2007	4.14	3.81	-0.66	0.96

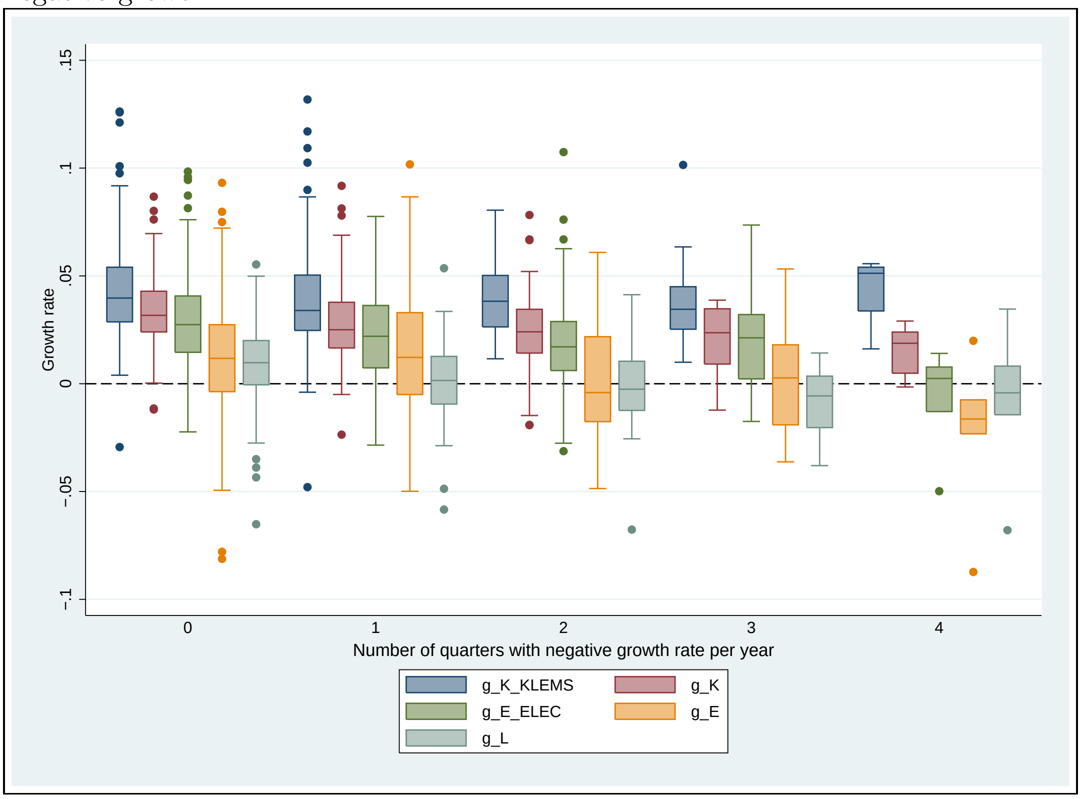
Notes: K_0 was constructed by applying a country-specific g_I and a depreciation rate of $\delta = 0.1$. Sample restricted to coverage of EU-KLEMS database.

Figure 5: Growth rates of K, E, E_{ELEC}, and L by number of quarters with negative growth



Notes: $\delta = 10\%$ and g_I = country-specific %.

Figure 6: Growth rates of K, K_{KLEMS}, E, E_{ELEC}, and L by number of quarters with negative growth



Notes: $\delta = 10\%$ and g_I = country-specific %. Sample restricted to coverage of EU-KLEMS Database.

Table 8: GDP and Total Factor Productivity Growth (depreciation rate: 10%)

						$\delta = 10\%$; g: country	
Country	Period	$\frac{\dot{Y}}{Y}$	$(2/3) * \frac{\dot{L}}{L}$	$(1/3) * \frac{\dot{E}}{E}$	TFP_E	$(1/3) * \frac{\dot{K}}{K}$	TFP_K
ARG	1972 – 2010	2.47	0.68	0.73	1.06	0.71	1.08
AUS	1961 – 2010	3.52	1.13	0.77	1.62	1.12	1.27
AUT	1961 – 2010	2.82	-0.21	0.79	2.24	1.21	1.82
BEL	1961 – 2010	2.71	-0.17	0.62	2.27	1.03	1.85
BGR	1990 – 2010	1.07	-0.72	-1.02	2.81	-0.02	1.81
BRA	1972 – 2010	3.36	1.43	0.99	0.94	1.25	0.69
CAN	1961 – 2010	3.31	1.11	0.72	1.49	1.35	0.86
CHE	1961 – 2010	1.87	0.29	0.69	0.89	0.87	0.71
CHL	1972 – 2010	3.91	1.71	1.11	1.09	1.36	0.84
COL	1972 – 2010	3.51	1.58	0.59	1.33	1.38	0.55
CYP	1988 – 2010	3.75	1.35	1.01	1.38	1.02	1.38
CZE	1991 – 2010	2.77	-0.06	-0.18	3.00	0.84	1.98
DNK	1961 – 2010	2.39	-0.01	0.47	1.94	1.21	1.20
ESP	1961 – 2010	3.58	0.39	1.30	1.89	1.64	1.55
EST	1991 – 2010	2.01	-1.37	-1.06	4.45	0.75	2.63
FIN	1961 – 2010	2.87	-0.17	0.69	2.35	1.01	2.03
FRA	1961 – 2010	2.84	-0.11	0.66	2.29	1.16	1.79
GBR	1961 – 2010	2.57	-0.15	0.16	2.55	1.11	1.60
GER	1971 – 2010	1.88	-0.34	0.03	2.19	0.39	1.83
GRC	1961 – 2010	3.35	0.00	1.50	1.85	1.49	1.86
HKG	1972 – 2010	5.57	1.29	1.19	3.09	1.99	2.28
HUN	1981 – 2010	0.99	-1.00	-0.18	2.17	0.40	1.59
IRL	1961 – 2010	4.07	0.24	0.91	2.92	1.60	2.23
ISL	1961 – 2010	3.11	0.64	1.19	1.29	1.29	1.18
ISR	1996 – 2010	3.34	1.51	0.84	0.99	1.08	0.75
ITA	1961 – 2010	2.65	-0.28	0.89	2.05	1.05	1.89
JAM	1987 – 2010	1.53	1.06	0.76	-0.30	0.84	-0.37
JPN	1961 – 2010	3.90	0.03	1.09	2.77	1.88	1.98
KOR	1972 – 2010	6.50	1.19	2.14	3.16	3.04	2.27
LTU	1994 – 2010	3.94	-0.50	0.13	4.31	3.27	1.17
LUX	1961 – 2010	3.80	0.75	0.56	2.49	1.15	1.90
LVA	1994 – 2010	3.74	-0.76	0.08	4.42	3.29	1.21
MEX	1972 – 2010	3.09	1.91	0.97	0.22	1.23	-0.04
MLT	1988 – 2010	3.44	0.53	0.47	2.44	0.84	2.07
NLD	1961 – 2010	2.87	0.10	0.99	1.79	1.04	1.74
NOR	1961 – 2010	3.28	0.23	0.79	2.26	1.01	2.04
NZL	1961 – 2010	2.43	1.01	0.86	0.55	0.99	0.43
PER	1972 – 2010	2.90	1.58	0.55	0.78	0.87	0.45
POL	1990 – 2010	3.86	0.44	0.20	3.21	0.98	2.44
PRT	1961 – 2010	3.43	0.37	1.28	1.78	1.58	1.48
ROM	1990 – 2010	1.58	-0.94	-0.94	3.46	-0.17	2.69
SGP	1972 – 2010	6.97	2.36	2.65	1.95	2.20	2.41
SVK	1990 – 2010	2.48	-0.86	-0.51	3.84	0.20	3.13
SVN	1991 – 2010	2.93	0.19	0.55	2.19	1.86	0.88
SWE	1961 – 2010	2.16	0.15	0.41	1.60	0.69	1.31
TTO	1992 – 2010	5.41	1.59	2.62	1.21	0.33	3.49
TUR	1961 – 2010	4.45	0.51	1.40	2.55	2.00	1.94
TWN	1972 – 2010	6.39	0.86	1.83	3.70	2.57	2.96
USA	1961 – 2010	3.00	0.84	0.41	1.75	1.25	0.91
VEN	1972 – 2010	2.06	1.84	1.22	-1.00	0.68	-0.47
Average	–	3.25	0.46	0.72	2.07	1.24	1.55

Table 9: Growth rate of TFP by year

Year	TFP_E	TFP_K	Difference
1961	3.33	2.77	0.56
1962	2.50	2.83	-0.32
1963	3.16	3.77	-0.61
1964	4.04	3.44	0.60
1965	2.45	2.18	0.27
1966	2.73	2.41	0.32
1967	2.75	2.36	0.39
1968	3.25	3.73	-0.48
1969	4.30	4.71	-0.41
1970	1.60	2.23	-0.63
1971	3.44	2.66	0.78
1972	2.99	2.94	0.04
1973	3.03	3.27	-0.23
1974	2.40	0.55	1.85
1975	0.64	-0.93	1.57
1976	1.96	2.75	-0.79
1977	2.54	2.26	0.28
1978	1.71	1.85	-0.14
1979	2.26	2.20	0.07
1980	2.48	0.83	1.65
1981	1.91	0.25	1.66
1982	0.82	-0.28	1.10
1983	0.75	0.57	0.18
1984	2.35	2.85	-0.51
1985	0.51	0.92	-0.40
1986	2.48	2.49	-0.01
1987	1.78	2.00	-0.22
1988	1.89	1.55	0.34
1989	1.47	1.18	0.30
1990	1.20	0.68	0.52
1991	0.78	0.37	0.41
1992	2.36	1.44	0.93
1993	2.06	1.72	0.34
1994	1.74	1.72	0.02
1995	2.69	2.55	0.15
1996	0.58	1.02	-0.44
1997	3.11	2.20	0.91
1998	1.74	0.74	1.00
1999	1.40	0.58	0.82
2000	3.43	2.71	0.72
2001	1.19	0.68	0.51
2002	2.01	1.27	0.74
2003	2.01	1.99	0.02
2004	2.68	2.53	0.15
2005	2.74	1.78	0.96
2006	2.71	1.82	0.89
2007	3.22	1.84	1.38
2008	0.92	-0.35	1.27
2009	-0.77	-2.48	1.71
2010	1.47	2.12	-0.65

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