WORKING PAPER SERIES

Aggregate Productivity under an Energy-Based Approach

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Abstract

Obtaining reliable data on capital is a recurring challenge when estimating economy-wide productivity growth, especially for developing countries. In this paper, I construct energy-based productivity series, which use energy consumption instead of capital when making such estimates. I first show that—for the U.S. and select OECD countries—growth in the energy-based series is strongly correlated with other sources historically. I then estimate energy-based productivity growth for other OECD and non-OECD countries where data on capital and productivity is more limited.

JEL Code: E00, O40, Q43

Keywords: total factor productivity, energy consumption, economic growth, international

1. Introduction

Growth in economy-wide productivity is an important determinant of long-run growth in real GDP per person, maybe the most important determinant (Easterly and Levine, 2001).[1] Conceptually, productivity is the efficiency of the production process, but in practice, it captures things that cannot be accounted for by capital and labor. A recurring challenge when calculating productivity growth is measuring and obtaining reliable data related to capital.

In this paper, I consider an alternative: using energy consumption instead of capital when calculating productivity growth to create an energy-based series (Bitzer and Goren, 2013). There are three distinct benefits to substituting energy consumption for capital when calculating productivity growth. Most important, data quality and availability in many countries makes obtaining trustworthy time series for capital problematic. This point is highlighted by the fact that even the EU KLEMS database has capital data only for 30 mostly developed countries (O'Mahony and Timmer, 2009).[2]

In contrast, in this paper I am able to use the energy-based approach in making comparisons of productivity growth for countries where capital data are not readily available. This is because historical energy consumption estimates are widely available, and if not perfect in quality, at least easier in theory to measure and project.

Second, using this approach allows an important role for energy in general, and energy consumption in particular, in accounting for productivity growth. Although the case that energy plays an important role in productivity growth has a long history (see Berndt (1990)), the recent focus has been elsewhere (see Stiroh (2001) for example). Finally, projections of energy consumption are widely available for many countries, as are projections of real GDP and labor supply. This means that energy-based productivity series can be calculated based on such projections—although I do not do so in this paper, something that generally cannot be done with data on capital.

Admittedly, the procedure suffers from several shortcomings, most notably the assumption that changes in energy consumption can proxy for changes in capital service flows. There is also the question of whether a total or sectoral measure of energy consumption is more appropriate in accounting for capital. The aforementioned concerns regarding data quality and availability apply here as well. Still, this is a simple and intuitive method that at the very least provides alternative estimates of productivity growth, and some estimates for countries or regions where capital data may be unavailable.

I begin with a brief overview of economy-wide productivity, discuss the standard way in which it is calculated, and then introduce the energy-based modification. Next, I show that historical estimates of U.S. productivity growth when energy consumption is used in lieu of capital are strongly correlated with a modified productivity series from the Bureau of Labor Statistics (BLS). The BLS series is modified for comparability—both the energy-based and modified BLS series use the same inputs for output, labor, and the capital share in estimating productivity growth. Comparisons between an energy-based and modified productivity series from the OECD for select OECD countries, over a shorter period, give similar

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[1] For a contrary view, see Jorgenson (1991).

[2] These are data on capital services. The Penn World Tables have capital stock data on roughly 60 countries.

results. I finish by using data on energy consumption to estimate energy-based productivity growth for other OECD and non-OECD countries.

2. Overview of aggregate productivity, its determinants, and calculation

Overview and Determinants

The standard concept of economy-wide productivity employed by macroeconomists is that of total factor productivity (TFP), also called multifactor productivity (MFP), which relates total output to a combination of inputs used in the production of that output. Conceptually, it is the efficiency of the production process, but in practice, it measures changes in output that cannot be accounted for by changes in combined inputs. These inputs include factors of production such as labor and capital, as well as intermediate goods and energy at the firm level.

Theoretically, growth in TFP is an important determinant of long-run growth in real GDP per person. However, because it measures things that cannot be accounted for by factors of production, identifying the driving forces behind TFP growth is difficult. In general, the candidate determinants can be separated between those which focus on the creation, transfer and use of knowledge, broadly defined, and those which allow for the creation, transfer, and use of that knowledge.[3]

TFP growth is often thought of synonymously with technological growth, but it can also be influenced by research and development, trade, foreign direct investment (FDI), organizational techniques, managerial practice, and improvement through experience (learning-by-doing), among other things. All of these determinants can be generally grouped by the fact that they create, transfer, or utilize knowledge (to include technology), and some provide more than one of these functions.

Creating, transferring, or utilizing knowledge presupposes the capabilities to carry out these activities. The determinants of such capabilities are also important drivers of TFP growth, and include human capital, health, institutions (including an innovation network), physical infrastructure, regulations (including trade and competition regulations), the cost of factor reallocation, the financial system (ability to match borrowers with savers), trade, and competition throughout the economy, among others.

Calculation

TFP growth is traditionally calculated as a residual (Solow, 1956). One first assumes an aggregate production structure for the economy; generally, that total output is produced using capital services, a labor input, and a catchall term often termed “technology”. The catchall term is equated to TFP, and its growth rate is implied historically by substituting for the presumably known growth rates of real GDP, capital services, and labor.[4] Both real GDP and simple labor input growth rates are available over long horizons for many countries. Historical capital services estimates are another matter.

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[3] See Syverson (2011) and Isaksson (2007) for more on the determinants of TFP at the firm and macro levels.

[4] To calculate TFP at any point in time (t), consider economy-wide output (Y) as a function of capital services (K), a measure of total labor input (L), and total factor productivity (A):

$$Y_t = A_t F(K_t, L_t)$$

Capital services refer to the flow of productive services provided by an asset that is employed in production. These flows over a period of time differ from the stock of physical capital at any given point in time. There are both theoretical and empirical issues with respect to measurement of capital service flows. Theoretically, one objection to measurement of the capital stock is that capital throughout the economy consists of heterogeneous goods that are not amenable to aggregation in physical units (Cohen and Harcourt, 2003).[5] There is also a concern of the proper theory which should be applied when converting the stock of capital into a service flow (Diewert, 2003). Practically speaking, there are problems associated with estimating aggregate depreciation or utilization rates as well.

These theoretical and empirical concerns can create substantial measurement uncertainty in calculating TFP. Moreover, given the resources necessary to make capital stock and services measurements, many developing countries do not have historical estimates of capital service flows. A simple and intuitive workaround is proposed by Bitzer and Goren (2013) in a recent working paper: substitute the growth rate of total energy consumption for the growth rate of capital services when estimating TFP growth. They argue that such a substitution overcomes the two primary concerns with measurement of capital service flows, as there is no aggregation problem and there is no need to convert from stocks to flows.

The intuition of Bitzer and Goren (2013) is that capital services can be viewed as the transformation of energy into ‘work’.[6] Thus, ‘work’ replaces capital services in the production function. To connect this idea to the standard calculation of TFP, they first relate energy input for ‘work’ to capital services. Energy input is then related to ‘work’ and a technology level. Using these relations they arrive at ‘work’ in terms of energy input and a technology level, hence energy consumption can be used in lieu of capital services.[7]

Take α as a parameter which represents total payments to capital as a share in total costs, with the remainder the share of labor costs and assume the production technology has constant returns to scale (doubling inputs leads to a doubling of output) and that firms maximize profits (or minimize costs). The equation above can then be logarithmically differentiated (where lower-case indicates logs and hats represent log changes from the previous time period) to give:

$$\hat{y}_t = \hat{a}_t + \alpha\hat{k}_t + (1-\alpha)\hat{l}_t$$

This equation can be rearranged in order to calculate TFP:

$$\hat{a}_t = \hat{y}_t - \alpha\hat{k}_t - (1-\alpha)\hat{l}_t$$

The expression clarifies that growth in TFP is calculated as a residual, given the capital share and the growth rates of real output, capital services, and the labor input. See Fernald (2015) for a full derivation that incorporates various adjustments to the utilization of capital and labor, as well as labor quality.

[5] This refers to the starting point for the so-called Cambridge capital theory controversies; see for example Cohen and Harcourt (2003). The general idea is that because capital is heterogeneous it cannot be aggregated in physical units but must be valued instead. Such valuation requires an interest rate, and the interest rate depends upon the capital stock. The importance of this circularity is still a subject of debate.

[6] ‘Work’ here is defined as in physics, i.e. the amount of energy transferred by a force acting through a distance.

[7] The approach of Bitzer and Goren (2013) begins by specifying economy-wide output as a function of ‘work’ (W) instead of capital services at any time (t):

$$Y_t = A_t F(W_t, L_t)$$

The primary concern with this approach is the assumption that capital services can be viewed as the transformation of energy into 'work'. Although the logic from this point forward is sound, it is unclear whether these concepts are so closely related. There is also the question of whether total energy consumption, as opposed to sectoral consumption, is a better measure of capital services. In addition, it is unclear how the magnitude of capital service flows correlates to the magnitude of energy consumption.[8] Finally, there are well known issues with measuring energy consumption in developing countries as well, although these may not be as substantial as with capital services.

Even with such issues, this is a powerful method. Not only is it simple and intuitive, but using energy consumption in lieu of capital services provides a method for implying productivity values when capital services data are unavailable. This is especially useful for developing countries. Additionally, where such data are available this method provides alternative estimates that highlight the importance of energy. The question of how the productivity estimates from this method compare to others historically is taken up in the next section.

3. Historical comparisons of the United States

This section compares two historical U.S. productivity growth estimates from 1950-2012.[9] The first is an energy-based productivity series calculated following the method of Bitzer and Goren (2013). Also considered are estimates based on capital service data from the BLS, called BLS productivity.

To make the series comparable, both use historical data on real output, hours worked, and capital shares from Fernald (2015) and calculate productivity growth as outlined in footnote 6.[10] The only differences are that the energy-based productivity series is calculated based upon total U.S. primary energy consumption data from EIA in lieu of capital services; the BLS productivity series uses capital services data from the BLS.

Figure 1 shows that the series tend to move together before 1980. The divergence after this point is most noticeable in the 1990s, although they appear to come back together around 2010. The figure also shows that the fluctuations in energy-based series productivity growth appear to be smaller than those from the BLS productivity series.

Where 'work' depends upon a technology level (Z) and energy consumption (E):

$$W_t = Z_t E_t$$

To link this with capital services, energy use is assumed to depend upon capital services, $E_t = F(K_t)$. Output can now be written as:

$$Y_t = A_t F(Z_t E_t, L_t)$$

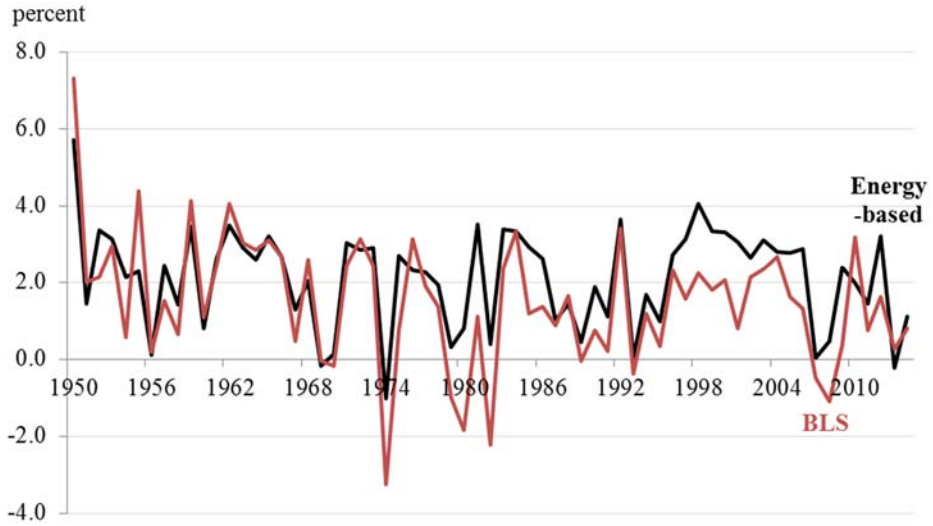
Once a functional form is assumed, the Z can be pulled out and incorporated into A, from which point its growth rate can be inferred using the procedure in footnote 4, except that the growth rate of total energy consumption is used instead of capital services.

[8] For example, a road provides a capital service when used by a car or truck. One might argue that the service flow is the same for both vehicles, but energy consumption by the truck is greater.

[9] See Gordon (2010) and Shackleton (2013) for more on U.S. productivity growth from the 1800s.

[10] See the historical data at http://www.frbsf.org/economic-research/indicators-data/total-factor-productivity-tfp/.

Figure 1: Comparison of growth rates for each U.S. productivity series, 1950-2014

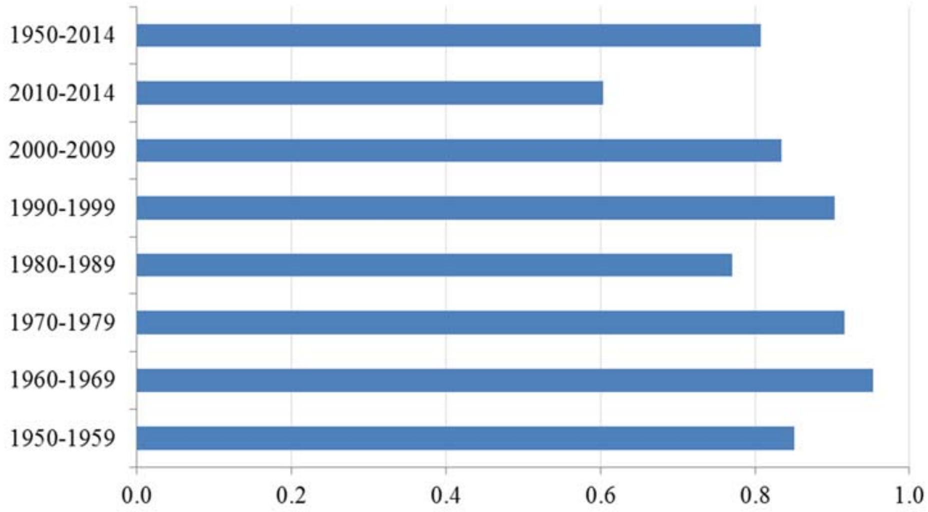


Source: Author calculations, BLS, Fernald (2015), EIA

The strong co-movement apparent from Figure 1 results in a relatively high correlation over the 1950 to 2014 period of 0.81 (Figure 2). It also appears that the strong correlation is not just an artifact of the long sample period: 10-year blocks between 1950 and 2014 also show strong co-movement.

This gets as high as 0.95 in the 1960s, although it drops to 0.6 from 2010-2014. Surprisingly, the correlation is still 0.9 in the 1990s when the series appear to move apart, and it is above the long-run average of 0.81 in each of the periods except for 1980-1989 and 2010-2014.

Figure 2: Correlations between growth rates in the U.S. productivity series, various periods



Source: Author calculations, BLS, Fernald (2015), EIA

On average from 1950-2014, energy-based productivity had the higher growth rate, at 2.1%—substantially larger than the 1.5% for BLS productivity. The BLS series, however, was more volatile, indicating relatively larger fluctuations in growth away from the mean, at 1.7% versus the 1.3% for energy-based productivity.

The historical comparisons provide some support for the claim that using total energy consumption in lieu of capital services provides reasonable estimates for U.S. productivity growth, at least in how it compares to a modified BLS series using the same output, capital share, and hours worked values. It is unclear how generalizable these results are to different periods in U.S. history. Still, they at least provide a plausible starting point for comparing such productivity growth series across various countries, and this is taken up in the next section.

4. Historical comparisons for Select OECD countries

This section compares two historical productivity growth estimates from 1986-2012 for select OECD countries. As above, the first is an energy-based productivity series calculated following the method of Bitzer and Goren (2013). The second are estimates based on capital service data from the OECD, called OECD productivity.

To make the series comparable for each country, both use historical data on real output and total hours worked from the OECD.[11] For convenience, I also assume the capital share is 0.35 in every year. The only differences are that the energy-based productivity series is calculated based upon the particular country's primary energy consumption data from EIA in lieu of capital services; the OECD productivity series uses capital services data from the OECD.

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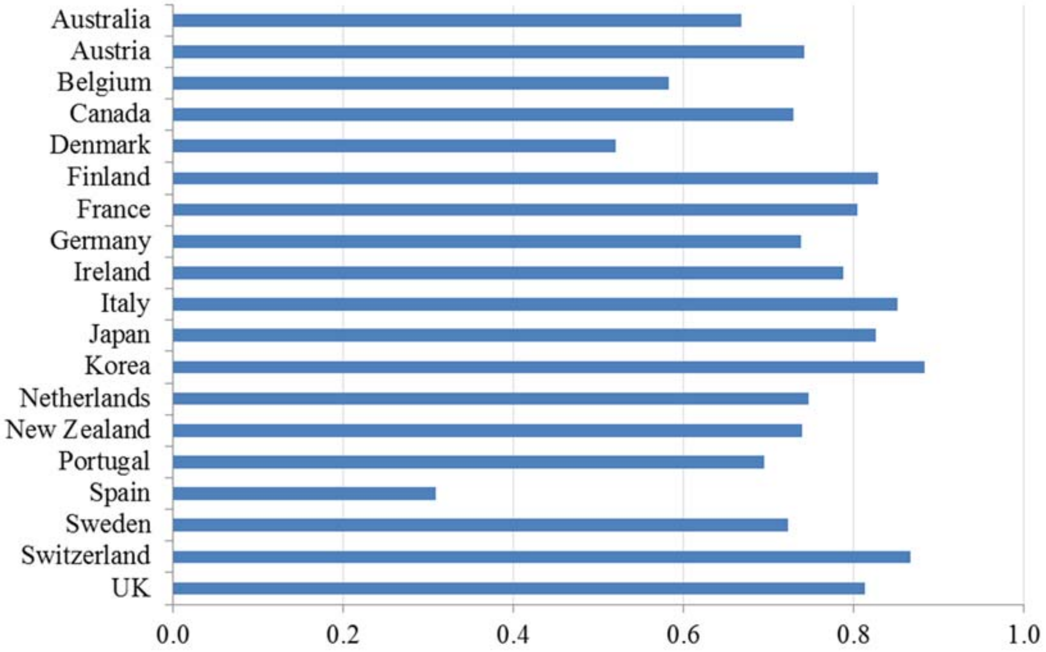
[11] See http://www.oecd.org/std/productivity-stats/.

As for the U.S., I can then calculate the correlations between growth in the two productivity series over the 1986-2012 time period (Figure 3).[12] As expected they vary by country, but most show a value that exceeds 0.6, and only Spain is below 0.5—although Denmark is close at 0.52.

Figure 3: Correlations between growth rates in the productivity series for select OECD countries, 1986-2012



Source: Author calculations, OECD, EIA

South Korea has the strongest correlation between growth in the energy-based and OECD productivity series (0.88). Switzerland is a close second at 0.87, and Finland, France, Italy, Japan, and the UK are all above 0.8. The remaining countries, other than Spain and Denmark, have values that range from about 0.58 (Belgium) to 0.79 (Ireland).

These correlations do differ from the ones calculated for the U.S. above, in that they can vary substantially when broken into smaller periods. Figure 4 shows the correlations in three, seven-year increments (86-92, 93-99, 00-06), and one six-year increment (07-12).[13]

It is difficult to generalize across the countries and time periods. Some, like Australia, Belgium, Canada, Germany, Italy, and Korea are relatively stable in the increments. Others, like Austria, Denmark, Finland, Portugal, and Spain display great volatility. The remaining countries fall somewhere in-between these two extremes.

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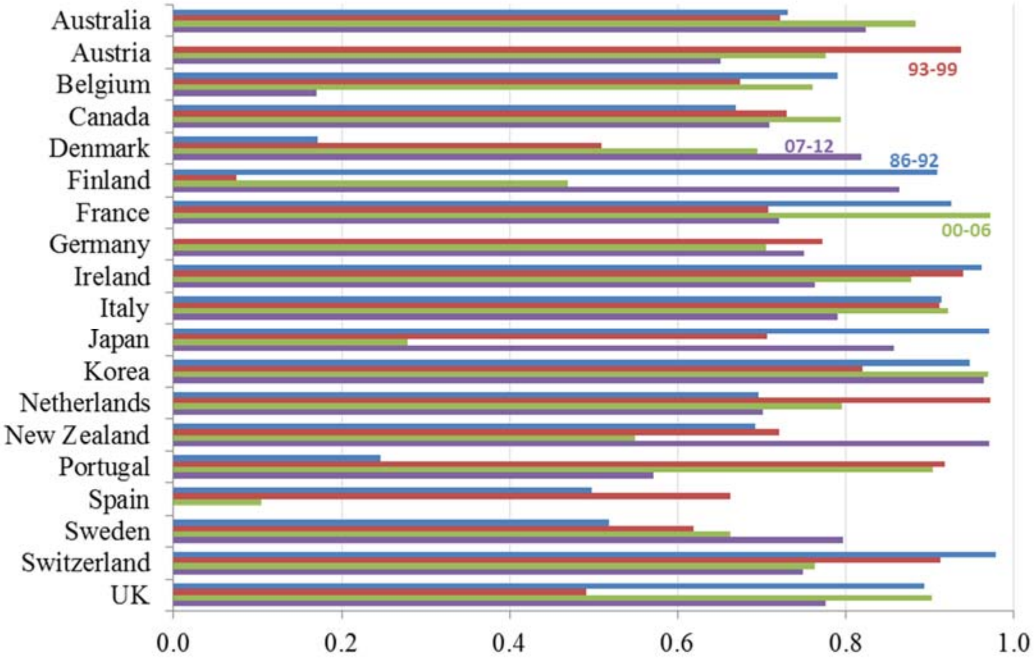
[12] Due to data limitations Austria begins in 1996, Germany in 1992, and Portugal ends in 2011.

[13] The correlation in Spain over the 2007-2012 period is not shown because it is very negative (-0.8) and makes the values for other series in the chart difficult to see.

Figure 4: Correlations between growth rates in the productivity series for select OECD countries, various time periods



Source: Author calculations, OECD, EIA

Another interesting feature of the correlations over the different periods is that some countries have stronger correlations early in the sample, and some later. For example, the co-movements of growth in the energy-based and OECD productivity series in Austria and Japan are larger from 1986-1992 than in any of the other periods. Moreover, the correlations in Denmark and New Zealand are bigger from 2007 to 2012 than in the other time increments.

As with the U.S., the historical comparisons of the implied productivity series for OECD countries—energy-based and OECD-based—suggest that energy consumption growth is a suitable stand-in for capital services growth when the latter is unavailable. I turn next to countries where capital services estimates are either unreliable or unavailable, and estimate historical productivity growth using energy consumption instead.

5. Historical productivity estimates for other OECD and non-OECD countries

Given that energy consumption projections appear to be an adequate substitute for capital services when calculating productivity growth in the U.S. and select OECD countries, I estimate historical productivity growth rates for other OECD and non-OECD countries in this section. As before, I derive the series using the procedure of Bitzer and Goren (2013). The other data—on hours worked and real output—are taken from Oxford Economics. I assume a capital share of 0.35 and use as much data as is available for the largest sub-set of countries, which turns out to be from 1995-2012.[14]

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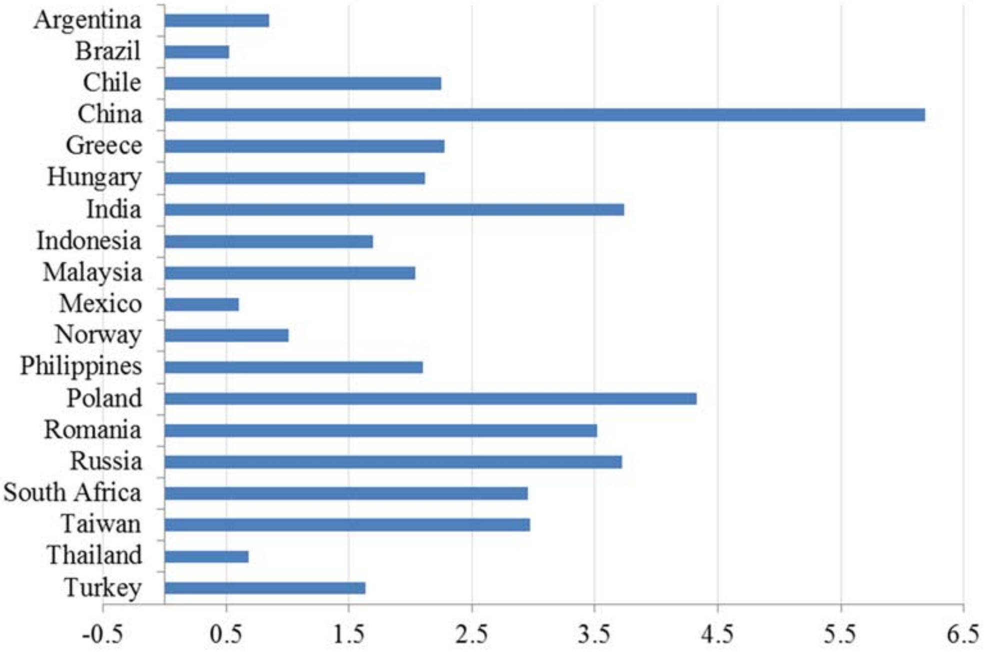
[14] Bulgaria and Saudi Arabia only have data beginning after 1995, and so the correlations are not shown for the entire period.

There is a good deal of variability in the average growth rate of the implied productivity series across the countries shown in Figure 5. As in many things, China stands out as the outlier: energy-based productivity growth averages nearly 6.2% per year from 1995 to 2012.

Figure 5: Average growth rates of energy-based productivity in select OECD and non-OECD countries, 1995-2012



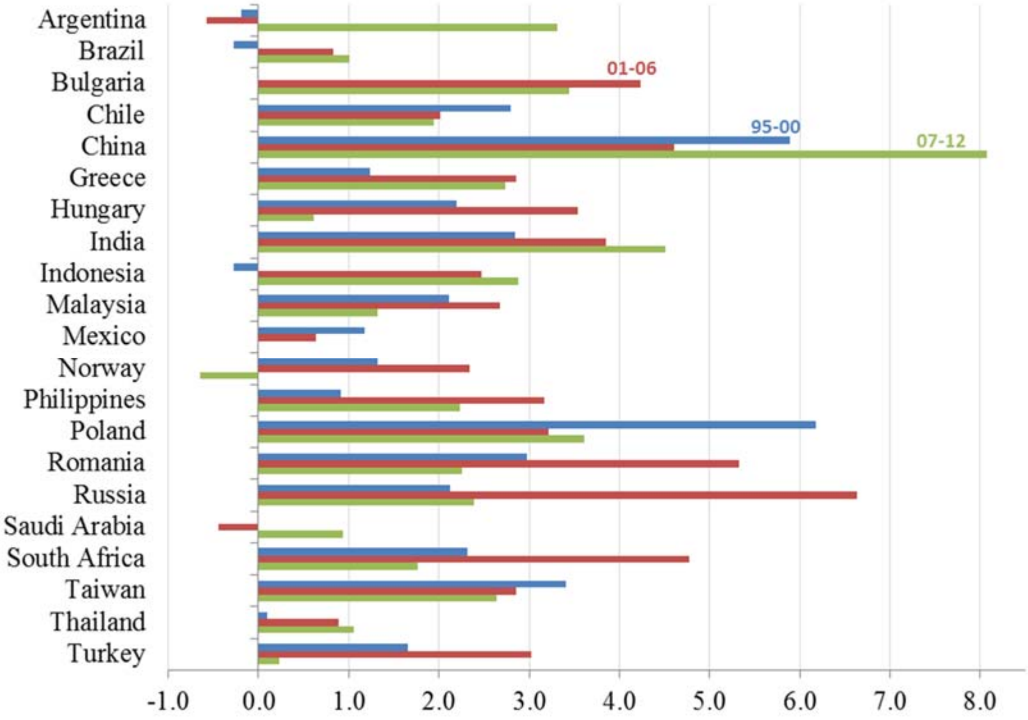
Source: Author calculations, Oxford Economics, EIA

Energy-based productivity growth in India, Poland, Romania, and Russia also appears to be fast compared to the other countries shown, at average rates of at least 3.5% per year.

Brazil brings up the rear: averaging energy-based productivity growth of just above 0.5% per year between 1995 and 2012. Mexico (0.6%), Norway (1%), and Thailand (0.7%) are not much better over this period. The difference between the highest (China) and lowest (Brazil) average growth rates is almost 6% per year.

When the periods are segmented into six-year increments, the differences are more pronounced (Figure 6). China does not have the fastest average growth in each of these periods—only between the years 2007 to 2012, at 8.1% on average. India, Argentina, and Poland all exceed 3% average growth during this time as well.

Figure 6: Average growth of energy-based productivity in select OECD and non-OECD countries, various periods



Source: Author calculations, Oxford Economics, EIA

Poland has the fastest average growth from 1995-2000, at 6.2% per year, while Russia has the highest between 2001 and 2006, at 6.6% annually. China, Chile, and Taiwan grow faster than 3% on average between 1995 and 2000, and Romania and South Africa show relatively quick growth in average productivity from 2001-2006.

On the low side, Indonesia and Brazil do the worst from 1995 to 2000: average energy-based productivity growth is -0.3% in both countries. Argentina's growth is also negative during this time at -0.2%, while Thailand barely grows, at 0.1% per year.

From 2001 to 2006, Argentina has the lowest implied productivity growth, around -0.6% each year. Saudi Arabia is also negative, falling more than 0.4% annually. Finally, Norway's implied productivity growth is the slowest over the 2007-2012 period, falling an average of 0.6% every year. Mexican implied productivity growth also falls slightly, while Turkey shows very slow growth.

In general, the productivity growth rates based on energy consumption show differences across countries and between periods. Given the challenges of estimating productivity in many of these countries, it is difficult to say how accurate they might be. Nevertheless, they do provide a relatively simple alternative to estimating capital service flows when making such calculations.

6. Conclusion

Measuring capital is a recurring challenge when estimating productivity growth. The use of energy consumption is a potential alternative. For the U.S. and select OECD countries—growth in such energy-based series are strongly correlated with other sources historically. Estimated energy-based productivity growth for other OECD and non-OECD countries, where data on capital and productivity is more limited, could fill some information gaps.

The benefits of this substitution are greater data availability, a resulting energy-focused productivity series, and the ability to calculate implied productivities for projections. The primary limitation is in gauging how well the substitution fits with accepted theory.

References

Berndt, Ernst R., “Energy Use, Technical Progress and Productivity Growth: A Survey of Economic Issues” *Journal of Productivity Analysis* 1990, 2:1, 67-83.

Bitzer, Jurgen and Erkan Goren, “Measuring Capital Services by Energy Use: An Empirical Comparative Study”, Oldenburg Discussion Papers in Economics, V-351-13, April 2013.

Cohen, Avi J. and G. C. Harcourt, “Whatever Happened to the Cambridge Capital Theory Controversies?” *Journal of Economic Perspectives* 2003, 17:1, 199-214.

Diewert, W. Erwin, “Measuring Capital,” NBER Working Paper 9526, 2003.

Easterly, William and Ross Levine, “What Have We Learned From a Decade of Empirical Research on Growth? It's Not Factor Accumulation: Stylized Facts and Growth Models,” *World Bank Economic Review* 2001, 15:2, 177-219.

Fernald, John, “Productivity and Potential Output Before, During, and After the Great Recession,” in J.A. Parker and M. Woodford eds., *NBER Macroeconomics Annual 2014*, Volume 29, p. 1-51, 2015.

Gordon, Robert J., “Revisiting U.S. Productivity Growth Over the Past Century with a View to the Future,” NBER Working Paper 15834, 2010.

Isaksson, Anders, “Determinants of Total Factor Productivity,” UN Research and Statistics Branch Staff Working Paper 02-2007, 2007.

Jorgenson, Dale W., “Productivity and Economic Growth,” in E. R. Berndt and J. E. Triplett, eds., *Fifty Years of Economic Measurement: The Jubilee of the Conference on Research in Income and Wealth*, Chapter 5973, 1991.

O’Mahony, Mary and Marcel P. Timmer, “Output, Input, and Productivity Measures at the Industry Level: The EU KLEMS Database,” *The Economic Journal, 2009*, 199: June, 374-403.

Shackleton, Robert, “Total Factor Productivity Growth in Historical Perspective,” U.S. Congressional Budget Office Working Paper 2013-01, March 2013.

Solow, Robert M., “A Contribution to the Theory of Economic Growth,” *The Quarterly Journal of Economics, 1956*, 70:1, 65-94.

Stiroh, Kevin J., “What Drives Productivity Growth?” *FRBNY Economic Policy Review, 2001*, March, 37-59.

Syverson, Chad, “What Determines Productivity,” *Journal of Economic Literature* 2011, 49:2, 326-365.