The Race for World Leadership of Science and Technology: Status and Forecasts

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Abstract

The US and EU have been vying for leadership of science and technology; now they are being overtaken by the People's Republic of China. The US is now leading in most input indicators, but the EU has taken the lead in important outputs. While the PRC remains behind in most indicators, its incredible progress from being underdeveloped during the Cultural Revolution to being a contender in this race is almost unprecedented. Qualitative assessment of fields of research and development, based on recent expert review studies, confirm that many Chinese labs have made rapid progress. Extrapolations from the current status and recent rates of change suggest that China will soon rival the others as a scientific superpower in many indicators. Further, a formal forecast of national publication shares can now be made, perhaps for the first time. The input to the model is a country's *share* of world R&D investment. If current trends in investment continue, the US and EU are forecast to continue to decline, while the PRC is expected to near parity with them within ten years in the Science Citation Index. Some confirmation comes from other databases—China has already passed the US in Inspec and Compendex.

Introduction

Since the 1950s, the top science goal of the U. S. Government has been "maintaining world leadership in science, mathematics, and engineering," and there is wide acceptance in the US of the premise that it remains ahead. Much of this confidence seems to depend on the US's spending more money on R&D than others. Even so, the US does lead the world in many science and technology (S&T) indicators when compared to much smaller single countries, but the emergence of a more coordinated European Union makes comparisons with the EU as a whole more realistic.

In 2000 the EU set a goal of becoming the most competitive and dynamic knowledge-based economy in the world by 2010. Strategies are being implemented to achieve this goal, including the tighter integration of research and development (R&D) activities into a European Research Area. While efforts to meet the EU goal to increase its investment to 3% of GDP by 2010 have been delayed, even this attempt compares favorably to the US, which has no national plan at all.

The PRC has plenty of plans, the most recent was the Mid- to Long-Term S&T Development Plan (2006 – 2020), which set a goal of doubling national R&D investment intensity to 2.5% of GDP by 2020--and that GDP has been growing at 10% or more for many years (State Council, 2006). Further, such goals are likely to be met, because the PRC has the resources and the national will to implement them, and because they merely represent a continuation of a long record of more than 15% annual increases in R&D investment. Even the 2008-9 financial crisis is not likely to derail this progress; at this writing, China claims to be continuing to grow fairly rapidly even as almost all other nations fall into recession.

Some bibliometricians were alert to China's sudden advance, and its rapid progress in output indicators like publications was documented early by Moed (2002), Jin and Rousseau (2005), and by Leydendorf and Zhou (2005). Indeed, this represents a success for the scientometrics community in detecting a global shift in science long before it became apparent to policy makers. Zhou and Leydesdorff (2006) have analyzed publications and citations to make the case that China must be already be considered a leading nation in science, particularly in nanotechnology.

This paper will update some of these indicators and provide additional ones: inputs like gross domestic expenditures on research and development (GERD) and human resources for R&D, plus outputs like publications, impacts, patents, science and engineering graduates, Nobel prizes, and high technology export market shares. For forecasting the future, the rate of change is at least as important, so the trend in terms of the average annual increase in the indicators over the last five years will also be calculated. Simple extrapolations then allow some insight into what is likely to happen in the race for world leadership during the next few years. A more formal model developed by the authors allows forecast of publication leadership from investment inputs. Of course, these forecasts were prepared at the very moment that the established trends were disrupted by discontinuous changes throughout the worldwide economy due to the Crash of 2008.

A tabulation of this kind of broader range of indicators was presented earlier when it was just the US and EU contending for the lead (Shelton and Holdridge, 2004). Larsen, Maye, and von Ins (2008) recently made a tabulation of publications and impacts for these countries, plus China, India and Japan. Shelton focused on finding the causes of what he called the American Paradox, the US decline in publication share despite huge and increasing investments in R&D (2008). Leydesdorff and Wagner have recently assessed the US leadership position, particularly in nanotechnology (2009). The European Commission periodically publishes a comprehensive report on EU progress toward its S&T goals, which contains many indicators (EC, 2007). The OECD Scoreboard report (OECD, 2007) and the NSF bi-annual Science and Engineering Indicators report (NSB, 2008) are other excellent sources. NSF provides more details in (NSF, 2007) and (NSF, 2007A). A recent RAND report (Galama and Hosek, 2008) attempts to make the case that US leadership is alive and well, however the bibliometric indicators used are somewhat dated—not a good idea when they are changing so rapidly.

Objective measurement of national leadership of S&T relies on a selection of these indicators of performance. *Quantitative* methods measuring inputs to the innovation process, such as annual research investments; and outputs such as technical papers and citations to them, patents, and international trade benefits of new technologies. This paper will first present tables of some of the most important indicators, then forecast the leading one: publications. *Qualitative* methods study the international stature of research efforts. These are peer reviews, and the best ones include *in situ* lab visits abroad. Such studies are expensive, and can cover only selected disciplines. However, the authors have organized over 60 such studies in the last 20 years through WTEC. This paper will also present a few findings from studies completed since 2005 that included study tours of the EU and/or China (WTEC, 2009).

Status of Indicators and Rates of Change

Inputs

Table 1 summarizes several national input indicators and their annual rates of change—each year's percentage change was calculated, and then the average of this parameter over the last five years is shown in parentheses. All data is for 2005 from (OECD, 2008). The rows will be discussed in turn; hopefully Europeans will not object if all three are called "countries," for short.

(Row 1) In total population these are very large countries indeed, so it is not surprising that they produce a lot of scientific output. Populations of all three are growing fairly slowly.

Table 1. S&T Input Indicators for 2005. (Average annual percentage rates of change in parentheses.)

Indicator	US	EU27	PRC	Units
1. Population	297 (1.0%)	492 (0.4%)	1308 (0.6%)	Millions
2. Researchers	1388 (1.0%)	1300 (3.1%)	1119 (10.6%)	Thousands
3. GDP	12376 (5.5%)	13031(4.4%)	5333 (12.9%)	Billions, PPP, current dollars
4. GERD	324 (1.7%)	227 (2.2%)	71 (18.9%)	Billions, PPP, current dollars, (Percentage in constant dollars)
5. GERD Share	36 (-2.0%)	26 (-1.5%)	7.8 (14.7%)	Percent of OECD Group (Percentage in constant dollars)

(2) Outputs of all kinds are produced by capital and labor. One labor indicator measured by the OECD shows that all three have comparable numbers of researchers, but China's research force has been growing much faster than the other two, despite the relatively static growth rate for its overall population.
(3) In terms of capital generation, the EU as a whole has the greatest gross domestic product, but the rate of increase in China is again remarkable. These GDP figures are weighted by purchasing power parity, an adjustment that attempts to equalize the real buying power of the local currency. Since they are in current dollars, real increases are reduced by inflation. In 2007 China passed Germany to become the world's fourth largest economy (behind the EU, US, and Japan), even when GDP is measured without the PPP weighting. For years, China has even been ahead of Japan when PPP weights are applied. (Based on much more economics than just this current growth rate, Albert Keidel of the Carnegie Endowment for International Peace believes that China will pass the US in GDP by 2035.)
(4) GERD stands for gross expenditures on research and development from all sources, a national investment statistic that has been collected for decades by the OECD at the points where R&D money is spent. The series in the table is in constant year-2000 dollars, so these are real increases, again with PPP weighting. And again the most striking number is the annual rate of increase in China; this growth rate has been doubling real R&D investment about every six years. (Later, Fig. 2 shows a column chart of this process in comparison to other countries.)
(5) One consequence of this rapid increase is shown in the last row. Despite the efforts of the US and EU to increase their R&D investment, China's share of GERD has rapidly increased at their expense. The basis for the percent share is the "OECD Group" of 30 member countries and 9 affiliates, which account for some 90% of worldwide GERD, because worldwide numbers are not accurately available. (Later, this will be illustrated in Fig. 3, and it will be shown that this input GERD share is a critical driver for output publication share.)

Outputs

Table 2 summarizes the most important output indicators; again, each row will be discussed in turn. (Row 1) The indicator that shows the most dramatic shift from the US to the EU and China is the number of technical publications in the world's leading journals as tabulated in the Science Citation Index (SCI). Since the SCI grows in size by the addition of new journals (and somewhat more papers per journal) by about 2.4% per year, the US and EU have declined in share because of the rapid increase of China, plus South Korea, Taiwan and Singapore. (Later, Fig. 5 shows this decline in share directly.) The causes of this sharp decline in the US share position have been studied by NSF for years, in terms of the equivalent levelling-off of total papers in the US. (NSB, 2008, p 5-36)

Space does not permit graphs of all these indicators (more are at http://itri2.org/Rpaper/.) One of the most interesting is included here: Fig. 1 shows the total number of papers in the SCI from the three countries. While China's rise is remarkable, it does not appear in this figure to threaten the leads of the EU and US, but read on. Perhaps the most important curve is *not* shown: the annual increase in the SCI itself, which can mask significant changes in national scientific output, which are better measured by *shares* of the SCI. (Decisions by Thomson Reuters to add journals to the SCI have very little to do with increasing productivity by anyone.) This rising tide tends to raise all boats, so when one is tied to the dock like the US during 1995-2002, it might sink. (To continue this metaphor well beyond good taste, a nation that is rising much faster than the tide, say China, might be a submarine surfacing.) Some in the US policy community feared that this stagnation in US growth, as it continued to pour money into R&D, might lead someone (like the Congress) to think that the US research system had saturated, and thus no increased investment was needed until the bottleneck resource had been identified. Years were spent searching for that bottleneck in the US (NSF, 2007A). Finally, some encouragement came from the small up-tick in US publication shown in Fig. 1 in 2003-5 (NSB 2008, p 5-36). However, it is easy to show that the up-tick simply comes from a considerably greater than usual increase in the size of the SCI database itself. We will see that one has to cast a wider net to find the cause of this American Paradox, abroad in fact.

Table 2. S&T Output Indicators, in 2005 unless noted in text. (Average annual percentage rates of change in parentheses.)

Indicator	US	EU27	China	Source
1. Quantity of Papers (SCI)	205320 (1.5%)	234868 (1.3%)	41596 (17.0%)	(NSB, 2008)*
2. Relative Impacts	1.47 (0.6%)	1.09 (1.1%)	0.63 (2.3%)	(ISI, 2006)
3. Triadic Patents	15774 (1.2%)	14571 (0.9%)	356 (35.1%)	(OECD, 2008)
4. S&E Ph.D. Production	26,275 (0.3%)	45,398 (2%)	14,858 (17.3%)	(NSB, 2008) (Moguérou, 2006)
5. Nobel Prizes (1950-2008)	168	260	3	(Braun, 2003) (Nobel, 2008)
6. High-Tech Exports, World Market Share in Percent	19 (-3%)	17 (0%)	15 (30%)	(EC, 2007)
7. Trade Balance (Goods in Billion Euros, current)	-666 (5%)	-127 (9%)	82 (45%)	(Eurostat, 2009)

* The SCI database itself increased by an average of 2.4% annually in 2001-5.

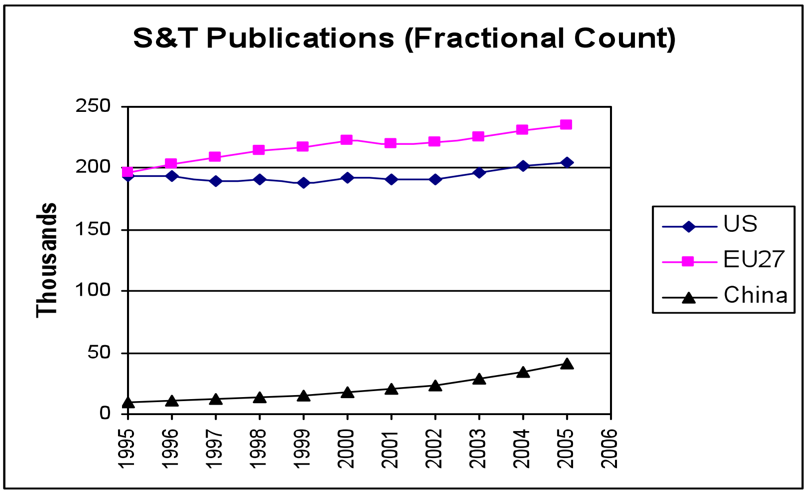

Figure 1. Publications in the Science Citation Index (NSB 2008)

(2) On the other hand, the US leads the EU as a whole in relative impacts (ISI, 2006). These normalized citation counts are a rough measure of the quality of technical papers. Compared to others, US researchers have an extraordinary propensity to cite mostly papers from their own country, which may distort this measure. Even so, some individual EU members lead the US in most of 20 technical fields in the NSI CD version of the SCI. Switzerland leads the world overall in relative impacts with 1.72 in 2005. China is far behind in this visibility measure of its papers, but is gaining slowly in this lagging indicator as its overall publication rate soars.

(3) Inventions are mainly patented in the home country of the inventors, which provides a "home court advantage" that makes it difficult to use this key output measure to compare the position of countries. Triadic patents are for inventions that are patented in three locations: the US, EU, and Japan, thus reducing the home country bias, among these three anyway (OECD, 2008). The US a small lead over the EU in this indicator, and again China is very far behind, but is coming up fast.

(4) While the total number of working scientists and engineers is an input resource to the R&D process, the production of new scientific personnel can be considered to be an output of the scientific establishment, particularly PhDs in science and engineering. In any event the EU has a huge lead in production of scientific human resources. However, the Chinese rate of increase again is remarkable—driven by a yet more rapid increase in investment in this sector, and there is no shortage of motivated and able students in China. The data is for 2004 from (NSB, 2008, Appendix Tables 2-40 bis), except the EU rate of change is from Moguérou, et al. (2006) though the year 2003.

(5) Nobel prizes are the gold standard of scientific achievement in the fields where they are given: physics, chemistry, and medicine. However, brain drain distorts this indicator somewhat. In recent decades, the career path of many Nobelists started outside the US, but by the time the award is made, they were living in the US. By birth location as shown, however, the EU has a big lead in the interval 1901-2005, while it may take centuries for China to catch up in this (very lagging) indicator. Data was taken from Braun (2003) through 2001, then Nobel (2008).

(6) Selling innovative products in the international marketplace is one bottom line of the innovation process. High technology production and its export are relevant indicators of the overall success of a country's S&T policies, although there are many other factors involved. A revealing chart in (EC, 2007, p 56) summarizes the trends in worldwide export market share. The US share has declined from 26% from 1999 to 19% in 2005. The EU curve is

essentially flat at 17% world market share. Again China is coming up rapidly—from 3% in 1999 to 15% in 2005, overtaking Japan, whose share fell to 9% in 2005.
(7) Overall international trade in goods is often used as an overall indicator of a nation's business and technological prowess in competing in the international marketplace. By this measure the US is leading the world, but in the enormous size of its trade deficit. The US deficit in 2005 was €666 billion, and that deficit was growing by about 5% per year. The EU also had a deficit of some €127 billion; a deficit that was growing at almost 9% per year. China had a *surplus* of €82 billion, which was growing at 45% per year (Eurostat, 2009).

Prior Work on Forecasting

While there are many objective indicators of the outputs of the national scientific enterprise, the one that is usually studied first is the number of scientific papers in the world's leading journals, whose peer selection process provides a measure of quality as well as quantity of research output. Indeed, the fierce competition by authors, institutions, and nations for the relatively fixed number of publication slots represents a free marketplace of ideas, where the best ones usually win.
The literature provides voluminous analyses of *past* publication data. Methods for forecasting *future* science indicators have received relatively little attention. A search of all *Scientometrics* issues for "forecast*" found only six hits, none really related to the problem at hand. *R&D Magazine* does annually make one-year forecasts of worldwide R&D investment (Battelle, 2008) based on surveys of large companies. One can, of course, merely extrapolate trends linearly, using as a slope and intercept the (mostly) year-2005 values in Tables 1 and 2. Forecasting 2010 results does not sound so daring, since that is only one year from this writing, but it is a five year leap from much of the available data. Still, for whatever it is worth, even linear extrapolations predict that China will soon assume leadership in two more indicators: researchers, and high-tech market share. That is, the leadership order would change in both indicators from US, EU27, then PRC in 2005--to PRC, EU27, then US in 2010. In one other indicator, PhDs in science and engineering, the PRC might be close to passing the US by 2010, although the EU is expected to continue to be well ahead of both.
Actually, using a linear forecast (an arithmetic progression) for Chinese indicators that are really growing exponentially (a geometric progression, like compound interest), is pretty conservative. Time series are posted at http://itri2.org/Rpaper/ where the difference between linear and exponential forecasts can be visualized. Here Fig. 3 shows a forecast of GERD share, based on a linear forecast of GERD increases that changes each year by the percent change given by the 1996-2005 average. Of course, GERD *share* has to be constrained to add to 100%, including all OECD Group countries.
Even such simple extrapolations have some value, because they draw attention to the short-term implications of China's rapid rates of change. However, models of the underlying causes can provide insight into how likely the trends are to continue. Using regression among the 39 countries with OECD data, to determine key input variables, can lead to models that can be validated, at least through "forecasting the past." Here the accuracy of one such a model developed by Shelton (2008) for data through 2003 is confirmed using financial input data through 2005 from OECD (2008) and fractional-count publication output data from NSF (2008). Similar models could be developed for other indicators, of course.

Model and Forecasts of Investment Inputs

The model forecasts output publication share from input shares of national R&D investment. Again, this is the GERD indicator collected by OECD for its 30 members and 9 affiliates (the "OECD Group"). The annual increases in GERD for 1996-2005 (in constant dollars) are shown in Fig. 2. The ten-year averages are 3.7% per year for the US, 2.9% for the EU27, and

19.1% for China. It is not surprising that these huge differences in R&D investments lead to profound changes in research outputs. (China's investments in science higher education appear to be at least as dramatic.)

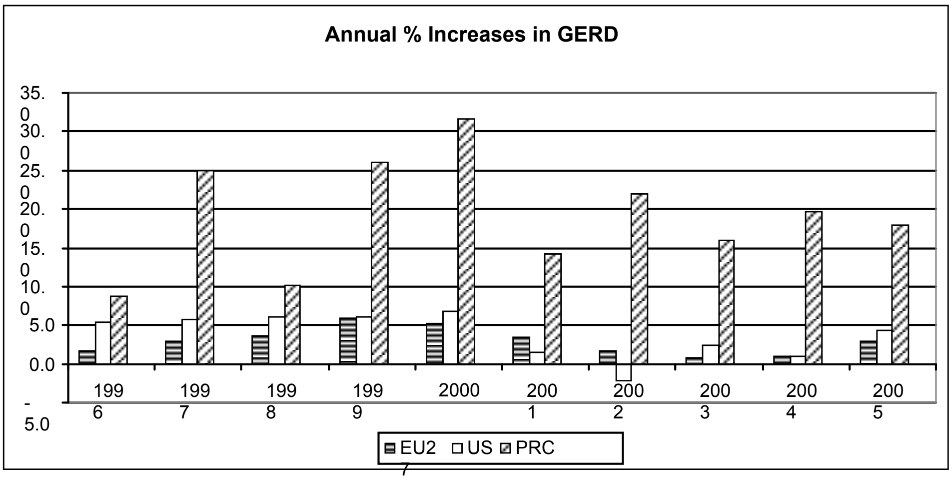

Figure 2. China's rapid increase in R&D investment.

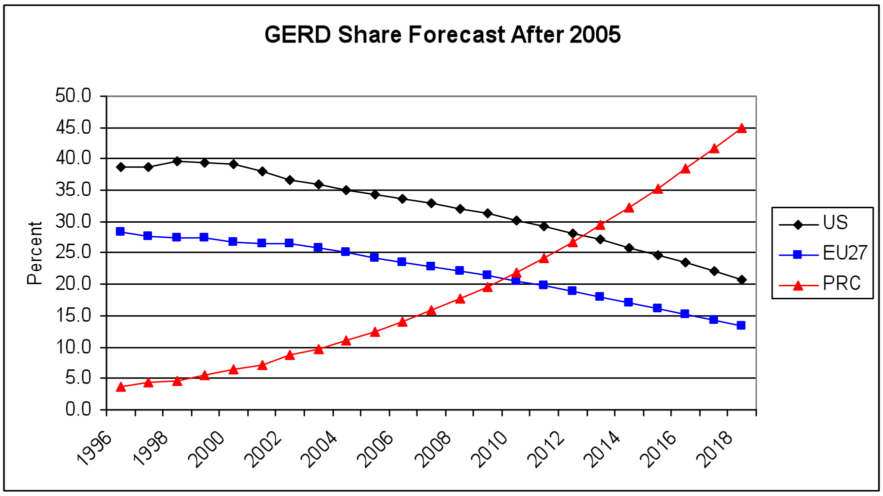

Figure 3. Forecasts of national R&D investment shares. GERD share of OECD Group in percent. (Historical data through 2005.)

Fig. 3 shows the GERD share obtained by dividing a nation's GERD by the OECD Group total, and forecasts that the average rates of GERD itself increase will continue linearly. (The PRC and US results for 2006 are already available, and are up 19.1% and only 2.7% over 2005, respectively.) The sums have to be constrained for all the OECD Group to add to 100%, of course. Here it is predicted that China will pass the US in GERD, and GERD share, by 2013 to lead the world in R&D investment.

Some confirmation of the future stability of these rates can be obtained from national strategic plans. Most significantly, China plans to double its R&D investment intensity (GERD/GDP) to 2.5% by 2020 ((State Council, 2006), and its GDP in the denominator has been growing at 10% or more per year. China has the resources to do this from its favorable balance of trade, and thus it seems likely that its rapid increases will continue. On the other hand, the EU effort to increase its GERD intensity seems to be faltering. The US has no national strategic plan at all for increase of overall R&D investments; the American Competitiveness Initiative and the

America COMPETES Act merely reallocate government agency investments. Thus an extrapolation of long-term trends seems reasonable. However, forecasting is always a dicey business. At this writing, many economic indicators have just seen sharp discontinuities due to the Crash of 2008. While the new Obama Administration seems committed to increasing public sector investment in R&D in the US, the worldwide recession is likely to make the private sector in most countries put off some long-term investments like R&D.

Forecasts of Publication Share Outputs

The model can be used to convert estimates of GERD share w_i for the i^{th} country, into publication share m_i:

$$\mathbf{m_i = k_i w_i}$$

The parameter k_i is called the "relative efficiency," since it can be shown to be the ratio of a country's efficiency at scientific publishing in papers per $1 million in research investment, normalized by the average of that efficiency (actually total papers divided by total GERD for the OECD Group). Shelton (2008) showed that the values of k_i were fairly constant for these three regions from 1998 to 2003, and this finding has now been extended in Fig. 4 through 2005. How constant is the k_i parameter? Over 1998-2005 the standard deviation as a percent of the mean is 4.2% for the PRC; 2.4% for the US, and 1.6% for the EU27. Thus, forecasts of paper share from GERD share may well be accurate. The 2005 values of k_i used for the forecasts later in Fig. 5 are 0.86, 1.41, and 0.71 for the US, EU27, and PRC, respectively.

These numbers are interesting in their own right; the EU is much more efficient in producing papers than the US, which is not so much more efficient than China with its recently changed PPP weight. Further, it is actually not common for the k_i curve for smaller countries to be so flat: some countries are improving their relative efficiency and vice versa. (Shelton and Foland, 2008)

The math model shows why it is the investment *share* that drives the shifts in publication *share*, and thence the overall publication indicator. Competing for a share of slots in journals is a zero-sum game: the sum of all the countries' shares always adds to 100%--using fractional counts of joint publications, of course. Multiple linear regression of the 39 OECD Group countries shows that the independent variable that is most predictive of the publication share dependent-variable is capital measured by GERD. Other variables like labor, measured by the number of researchers, turn out not to be statistically significant in the multiple regression. Most nations are increasing their GERD, so how can it be that some nations like the US are losing publication share, or equivalently, have a fairly static count of total publications as the size of the database increases? Using wild assumptions for building the model, like editors selecting papers from a country in proportion to the number submitted, and the number submitted from a country being proportional to its GERD, Shelton shows that it is the zero-sum GERD share that determines the zero-sum publication share. Something like this relation is necessary in order for the units of the variables to be consistent regardless of those assumptions. More importantly, the experimental results in Fig. 4 for the big players show that the model is consistent with reality. While it differs by country, k_i is pretty close to being a *constant* of proportionality for these three after 1998, and thus GERD share drives publication share between them.

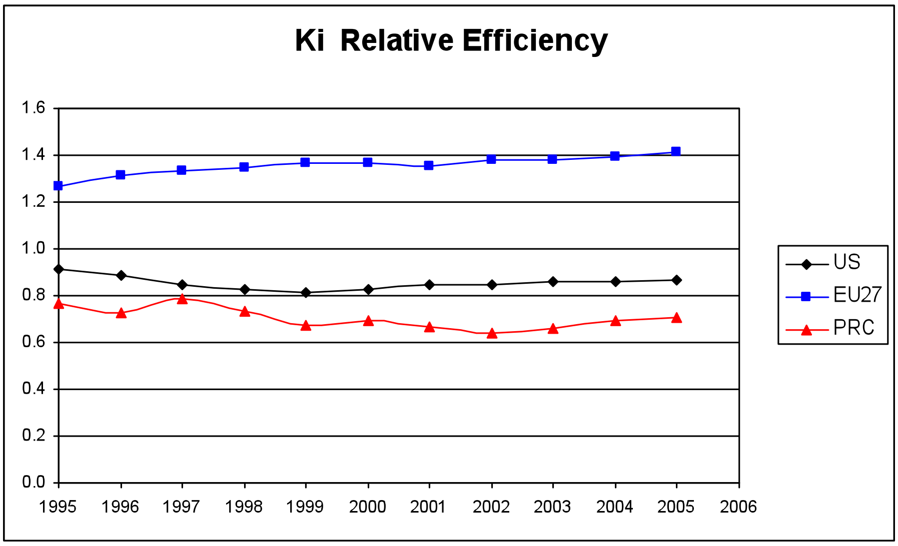

Figure 4. Accuracy of model. Over intervals when the curves are fairly flat, GERD share is the driver for paper share.

The forecasts in Figure 5 show that China's gain at the expense of the US and EU in scientific publication is expected to continue. The curves are publication share in percent of the OECD Group, which publishes nearly 90% of the SCI and SSCI. Fractional counting of joint authors is used. The crossover where China is forecast to take the world lead is sensitive to the forecast rates of GERD increase. It is fair to say though, that if present trends continue, the PRC will near parity with the US and the EU in scientific publication in less than ten years from this writing.

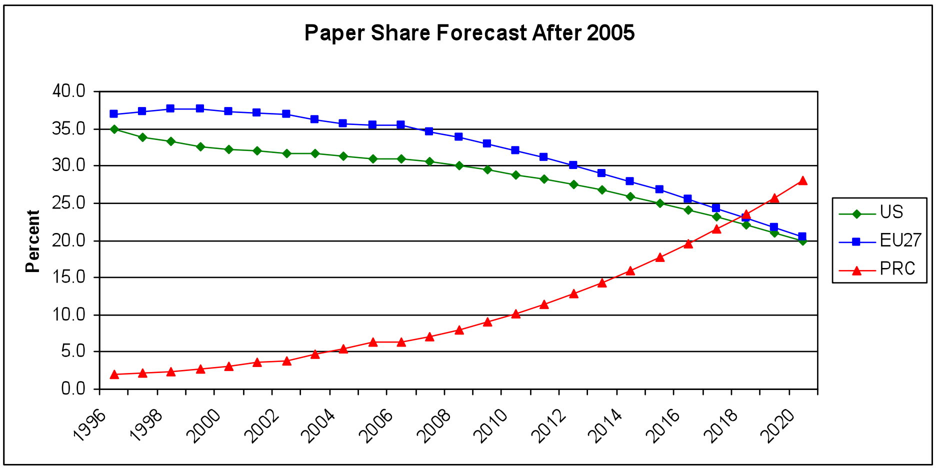

Figure 5. Forecasts of scientific publication share (after 2005) using forecasts of GERD share input to the model.

Bibliometricians may not find this forecast to be so surprising, since it can be foreseen merely by extrapolating China's well-known exponential rise in publications. However, those in the US who believe that it is "maintaining its lead in S&T," may find it hard to believe that a country that was so underdeveloped in science so recently may soon come to surpass the US in this key indicator. So, to corroborate this message, publication counts from other databases may be useful. Scopus shows that China with about 203,000 publications was far behind the US with some 369,000 in 2007, but the trend lines also cross in the middle of the next decade.

Kostoff (2008) has also recently confirmed this message using the Inspec and Compendex (mostly physical sciences) databases, as well as SCI. He found that China has already passed the US overall in the first two databases by 2007. He also considers leadership in 30 particular technologies like composites, catalysis, X-ray diffraction, and photoluminescence. (In these four fields, China has already passed the US, even in the SCI.) Kostoff does not present data on Europe. Here Fig. 6 shows that, although China passed the US in 2007, the EU27 still led China overall in the Inspec database in 2007, but probably not for long. (The Inspec results are based on the nationality of only the first author.)

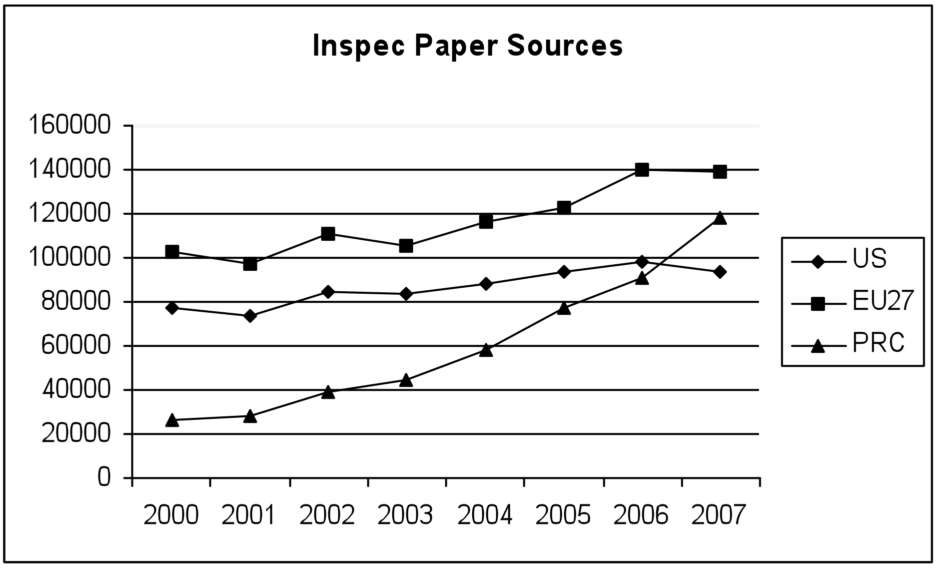

Figure 6. National sources of papers in the Inspec database

Conclusions

A simple summary of the current status of the indicators selected here also makes it sound like the US lead is alive and pretty well; it leads in researchers, GERD, patents, impacts, and high technology exports. However, the EU leads in GDP, SCI publications, Nobel prizes, and PhD production. China leads only in overall international trade balance, and that vast population of producers and consumers. But, as shown by the forecasts, the trends are very unfavorable for the US and the EU. They show that it is just a matter of time--short for leading indicators like the number of researchers, and longer for lagging ones like patents--until China will be a scientific superpower comparable to the US and EU, and perhaps lead the world by a reasonable selection of indicators.

Only a paradigm shift could disrupt this process. The current financial crisis may slow, or even speed, China's relative progress. Or politicians in Western nations could wake up to this emerging challenge to their scientific leadership and do something about it. If Shelton is right about GERD share being the driver, the only realistic remedy for loss of leadership in publications (and perhaps for other indicators) is by matching China's rapid increases in R&D investment. (Trying to gain share by increasing national efficiency in papers per dollar invested, as some smaller nations have done, is even more difficult for these huge science establishments.) Thus Western nations would have to make a substantial reallocation of budgets toward this kind of long-term investment—by both governments and industry.

Sounds impossible? Of course, this is just what has been done in China, South Korea, Taiwan, and Singapore.

Some are sceptical of such findings about China's progress toward world leadership of science and technology. They cite visits to Chinese labs that merely follow Western science, or speak of their (current) low rate of other output indicators like citations or patents. However, some confirmation of these quantitative findings comes from recent qualitative studies of R&D in China. Since 2005 WTEC has sent four peer-review delegations to the PRC on simulation, carbon nanotubes, catalysis, and brain-computer interfaces; reports are posted at (WTEC, 2009). This small sample tends to confirm these trends; delegations always are struck by how rapid Chinese progress is. Only very recent witnesses can be up-to-date.

Is China's rapid growth in S&T really unprecedented? Like China in 1976, Japan in 1854 was deliberately isolated and backward in the day's technology. Afterwards, Japan made incredible progress in industrializing to the point that they could defeat a Great Power (Russia) in 1905 using the highest technologies of the day. Japan also quickly went from rags to riches after World War II by manufacturing for export, then using the profits to achieve self-sufficiency in technology. In planning the recovery from the wreckage of the Cultural Revolution in the late 1970s, Deng Xiaoping clearly had in mind Japan's successes, and other similar ones in the region.

Since science itself is much more than a zero-sum game, everyone should appreciate that the Chinese are making huge and rapidly increasing investments in science and in science education, and are starting to reap the output benefits, which benefit all mankind. Westerners only wish their governments could be so wise in their investments – for even greater benefit to mankind.

Acknowledgements

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