Comparative Study of Major Science and Technology Indicator Systems for Sci-tech Powerhouses: Postprint

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Abstract

China has proposed strategic goals for science and technology development to rank among the forefront of innovative countries by 2035 and to build a world science and technology power by 2050, necessitating in-depth research on what quantitative and qualitative indicators can be used to describe being among the forefront of innovative countries and a world science and technology power. This article focuses on the strategic goals and tasks proposed by China to rank among the forefront of innovative countries and build a world science and technology power, and based on major representative indicator systems and research reports on international national competitiveness and innovation capability evaluation, systematically identifies important and typical science and technology indicator frameworks for describing a world science and technology power. Through horizontal benchmarking analysis of performance across major indicators against world science and technology powers such as the United States, it reveals China's performance and gaps in major science and technology indicators, and proposes quantitative and qualitative indicator targets for China to rank among the forefront of innovative countries by 2035 and to become a world science and technology power by 2050, along with relevant development recommendations.

Full Text

Abstract

China has proposed strategic goals for scientific and technological development: to join the ranks of innovative countries by 2020, to be among the front-runners of innovative countries by 2035, and to become a world science and technology power by 2050. Achieving these objectives requires in-depth research into the quantitative and qualitative indicators that define a leading innovative country and a science and technology power. This paper examines China's strategic goals and tasks of joining the forefront of innovative countries and building a world science and technology power. Based on major international indicator systems and research reports on national competitiveness and innovation capacity, we identify and analyze important and typical scientific and technological indicator systems that characterize a science and technology power. Through horizontal benchmarking analysis with world science and technology powers such as the United States across major indicators, we reveal China's performance and gaps on these key metrics. We propose quantitative and qualitative indicator targets for China to join the forefront of innovative countries by 2035 and to build a world science and technology power by 2050, along with relevant development recommendations.

Keywords: innovative countries, science and technology power, evaluation indicator system, scientific and technological evaluation indicators

1. Basic Understanding of Science and Technology Powers

German business theorist Von Hornig once noted, "Whether a country is currently prosperous does not depend on its own strength and wealth, but mainly on the strength and wealth of its neighboring countries." Thus, a country's strength is determined not primarily through vertical comparison with its own history, but through horizontal comparison with other nations, and such comparison should be comprehensive. However, given the focus of this paper, we discuss only from the scientific and technological perspective.

A world science and technology power must satisfy three fundamental conditions. First, it must be an innovative country. Currently, based on internationally recognized ranking systems for innovative countries, there are approximately 20–25 such nations. However, these indexed rankings represent equalized results that obscure two critical factors: national scale and population size. Some highly-ranked small countries (with small populations and territories) do not align with common perceptions of a science and technology power. A world science and technology power must possess overwhelming advantages in major scientific and technological fields and should be a powerhouse of original knowledge output, technological output, and creation of new technology industries.

Second, a science and technology power requires certain scale and size, including substantial territorial space, population, and economic scale. Small innovative countries cannot become universally recognized science and technology powers due to their limited territory, population, and incomplete scientific and industrial systems, although their innovation experiences may offer valuable lessons. As Feng Jiangyuan pointed out, becoming a regional or global power is a prerequisite for becoming a strong power.

Third, today's major science and technology powers are primarily five countries: the United States, United Kingdom, Germany, France, and Japan. The UK, France, Germany, United States, and Japan each seized opportunities from the first three industrial revolutions to become internationally recognized world science and technology powers. While the Soviet Union was undoubtedly a world science and technology power, Russia has clearly fallen behind. Therefore, the current world science and technology powers are the United States, United Kingdom, Germany, France, and Japan. These powers form two echelons: the United States stands alone in the first echelon, while the others constitute the second echelon, with the United States being the true leading world science and technology power. Consequently, China's benchmark countries for becoming a world science and technology power can only be these five internationally recognized major powers, fundamentally the United States.

Accordingly, this paper selects the United States, United Kingdom, Germany, France, and Japan as benchmark countries to examine the main scientific and technological indicators employed in authoritative international evaluation systems of national innovation capacity and competitiveness. We reveal the development trends of world science and technology powers on these major indicators, observe China's development gaps and directions for improvement, and attempt to propose quantitative and qualitative indicator targets for China's science and technology power construction.

2. Main Scientific and Technological Indicators of National Innovation Capacity

To effectively evaluate and compare national/regional innovation capacity and competitiveness, numerous international organizations and academic institutions have developed various evaluation indicator systems and published a series of assessment reports. This paper analyzes eight influential and comprehensive evaluation indicator systems and research reports on national innovation capacity and competitiveness, examining their indicator frameworks, characteristics, coverage, and annual results to extract science and technology-related indicators .

Although these evaluation systems differ in perspective, analytical level, and focus, their dimensions can generally be summarized as: policy and institutions, infrastructure, scientific research and development, financial investment, human capital, and knowledge assets. Except for the *World Competitiveness Yearbook*, which requires payment for access and thus was not analyzed in detail, we examined each indicator from the remaining seven reports to extract those closely related to "scientific research and development" . The main scientific and technological indicators in these evaluation systems include: R&D investment intensity, R&D personnel ratio, quantity and impact of scientific papers, international patent applications (PCT), intellectual property payments and receipts, and high-tech imports and exports.

From three of the most representative innovation capacity/competitiveness reports (*Global Competitiveness Report*, *World Competitiveness Yearbook*, and *Global Innovation Index*), China's global ranking in innovation capacity/competitiveness has shown an overall upward trend over the past five years [Figure 1: see original paper], gradually entering the ranks of innovative countries.

3. Performance of China's Innovation Capability on Main Scientific and Technological Indicators

To join the forefront of innovative countries and build a world science and technology power, China must continuously narrow the significant gaps with developed countries or achieve comparable levels in major scientific and technological indicators closely related to the "scientific research and development" dimension, including Nobel Prizes, field-specific scientific awards, highly cited scientists, paper and patent output, top 100 enterprises and universities, R&D investment intensity, R&D personnel ratio, high-tech product exports, and intellectual property transfer.

3.1 Nobel Prizes in Science

As of October 2017, the three Nobel science prizes (Physics, Chemistry, and Physiology or Medicine) have been awarded 328 times to 596 laureates from 27 countries [Figure 2: see original paper]. Over 50% of these prizes were awarded to American scientists (172 times). Other countries with more than 10 awards include the United Kingdom (73), Germany (61), France (28), Switzerland (19), Sweden (15), and Japan (14). China (including Hong Kong) has received 2 awards: Tu Youyou (2015) and Charles Kao (2009).

Notably, Japan's "Nobel Prize Plan" illustrates strategic foresight. In its second Science and Technology Basic Plan (2000), Japan aimed to "win 30 Nobel Prizes in 50 years." By 2017, Japan had already secured 14 Nobel science prizes (some counts show 17, but 3 laureates were US citizens at the time of award). In recent years, Japan has averaged nearly one Nobel laureate annually, demonstrating steady progress toward this ambitious goal.

3.2 International Science and Technology Awards

International awards in science and technology directly reflect national innovation capacity in specific fields. To understand countries' performance, we conducted quantitative analysis of 23 representative major international science and technology awards across eight fields: basic and interdisciplinary frontiers, advanced materials, energy, life and health, oceans, resources and ecological environment, information, photonics and space, and comprehensive areas and [Figure 3: see original paper].

Since their inception through 2018 (statistics as of September 30, 2018), these 23 awards have been granted to 2,078 individuals (or teams). Among them, 33 laureates hold multiple nationalities (counted once per country, totaling 2,117), and nationality information for 9 foreign scholars is unavailable.

The data show that US-affiliated laureates lead overwhelmingly with 1,144 individuals, accounting for 54% of the total. Other major countries include the United Kingdom (277), Canada (92), France (88), Germany (67), Russia (65), and Japan (59). China (including Hong Kong, Macao, and Taiwan) has only 14 laureates.

Chinese laureates are distributed across only five fields: photonics and space, information, resources and ecological environment, oceans, and life and health. These include: Liu Jiyuan and Wu Meirong (2011 and 2013 Von Kármán Awards), Andrew Yao (2000 Turing Award), Te-Tzu Chang and Tungsheng Liu (1999 and 2002 Tyler Prize for Environmental Achievement), Ye Duzheng, Qin Dahe, and Zeng Qingcun (2003, 2008, and 2016 IMO Prizes), Shang-Ping Xie (2017 Sverdrup Gold Medal Award), Tu Youyou (2011 Lasker Medical Award), He Kang and Yuan Longping (1993 and 2004 World Food Prize), and Yuan Longping and Shang-Fa Yang (1991 and 2014 Wolf Prize in Agriculture).

China's performance in international science and technology awards is unsatisfactory, with significant gaps compared to major developed countries, particularly in disciplinary distribution. While the United States has laureates across all technological fields, especially basic sciences, life and health, information, and oceans/resources/ecological environment, China's distribution is notably limited.

3.3 Highly Cited Scientists

Analysis of Clarivate Analytics' "Highly Cited Researchers" lists from 2014–2017 shows the United States leads by a substantial margin, followed by the United Kingdom, Germany, China, and Japan. China rose to fourth place in 2016 and third place in 2017, surpassing Germany.

Comparing the distribution of highly cited scientists across disciplines among the United States, China, the United Kingdom, Germany, and Japan reveals that the US far exceeds the other four countries in nearly all fields. China's distribution is extremely unbalanced, with significant gaps compared to the US, UK, and Germany. China's strengths are concentrated in materials science, engineering, and chemistry, while fields such as space science, social sciences, and psychiatry/psychology have almost no representation. The top five Chinese institutions by number of highly cited scientists are the Chinese Academy of Sciences, Tsinghua University, University of Hong Kong, China Medical University (Taiwan), and Peking University.

3.4 Paper and Patent Output

Data from Clarivate's Essential Science Indicators (ESI) database show that from January 1, 2008, to February 28, 2018 (retrieved March 20, 2018), China published approximately 2.168 million papers, ranking second globally—about half of the US total (ranked first) and roughly double Germany's total (ranked third). The gap between China and the US continues to narrow. For instance, Web of Science statistics show China published 428,000 papers in 2017, still ranking second and reaching two-thirds of the US volume. However, China's average citations per paper (reflecting academic impact) is significantly lower than that of the US, UK, Germany, France, and Japan—approximately half that of the US and UK (ranked first and second)—indicating that while China's scientific output has grown rapidly, research quality still lags considerably.

In 2017, China's Patent Cooperation Treaty (PCT) applications rose to second globally for the first time. However, when measured by "PCT applications per 10 billion USD GDP (PPP)" [21], China's performance (2.1 applications per 10 billion USD GDP) slightly exceeds the UK's (1.9) but remains substantially behind the US (2.9), Germany (4.6), France (2.8), and Japan (8.9) [Figure 4: see original paper].

3.5 Top 100 Universities and Technology Enterprises

Despite China's total paper count, highly cited paper count, and highly cited scientist count all ranking within the global top three, China lacks world-leading universities and world-class technology enterprises commensurate with these aggregate figures.

For example, in the 2018 QS World University Rankings, only six Chinese universities (excluding Hong Kong, Macao, and Taiwan) entered the top 100, with Tsinghua University ranking highest at 25th. The US consistently has approximately 30 universities in this top 100 list. In the 2018 Times Higher Education World University Rankings, only two Chinese universities entered the top 100, with Peking University at 27th and Tsinghua at 30th, while the US consistently has over 40 universities in the top 100.

In Clarivate's January 2018 list of "Top 100 Global Technology Leaders," only Huawei from mainland China was included. In Clarivate's April 2018 "2017 Top 100 Global Innovators," Japan and the US accounted for 75%, establishing themselves as genuine global innovation centers, while China again had only Huawei included.

3.6 R&D Investment Intensity

China's R&D investment intensity has steadily increased from 0.90% in 2000 to 2.11% in 2016, reaching 2.12% in 2017, with basic research accounting for 5.3% of total R&D expenditure. In 2016, the US, Germany, France, and Japan had R&D intensities of 2.74%, 2.94%, 2.25%, and 3.14%, respectively [Figure 5: see original paper]. The countries with the highest R&D intensities globally are Israel and South Korea, at 4.25% and 4.24%, respectively [22].

3.7 R&D Personnel Ratio

The proportion of R&D personnel in the employed population is another crucial indicator of national innovation capacity. As shown in [Figure 6: see original paper], in 2016, China's R&D personnel accounted for 0.218% of total employment, while the corresponding figures for the US, UK, Germany, France, and Japan were 0.914% (2015), 0.918% (2016), 0.919% (2016), 1.012% (2015), and 0.996% (2016), respectively. The countries with the highest R&D personnel ratios are Israel and Denmark, approaching or exceeding 1.5% (2016) [23].

Given China's large population base, it may be unrealistic to pursue top global rankings in this indicator. However, to join the forefront of innovative countries and build a science and technology power, China must still increase its R&D personnel ratio and expand its R&D workforce to a certain extent.

3.8 Intellectual Property Trade Balance

International receipts and payments for intellectual property (IP) use are core indicators of a country's market-oriented knowledge value creation capacity. China has consistently run a deficit in IP use fees, indicating it is not yet a strong creator of valuable intellectual property. According to IMF statistics [24,25], in 2017, China's IP receipts were $4.779 billion, while payments reached $28.661 billion, resulting in a deficit of $23.882 billion. In contrast, US IP receipts totaled $128 billion with payments of $48 billion, yielding a surplus of $80 billion and establishing the US as the strongest IP creator and value-realization power. The UK, Germany, France, and Japan also maintain IP trade surpluses.

US Bureau of Economic Analysis data show the US has consistently run an IP surplus with China, growing from $1.825 billion in 2007 to $7.415 billion in 2016. According to China's State Council Information Office white paper "The Facts and China's Position on China-U.S. Economic and Trade Friction" (September 24, 2018), China's IP payments to the US increased from $3.46 billion in 2011 to $7.2 billion in 2017, figures consistent with the US data.

These trends demonstrate that China's technological innovation remains at a stage where most technologies are purchased from foreign sources. China urgently needs to strengthen IP creation, protection, and utilization capabilities and cultivate high-value patents. To join the forefront of innovative countries and become a science and technology power, China must achieve at least an IP trade surplus.

4. Main Scientific and Technological Indicators for Joining the Forefront of Innovative Countries and Becoming a Science and Technology Power

The main scientific and technological indicators of a science and technology power constitute the primary markers and directions for building an innovative country. These indicators should include both quantitative and qualitative aspects.

Based on the above analysis, for China to join the forefront of innovative countries by 2035 and build a world science and technology power by 2050, it must continuously improve on the following quantifiable indicators: R&D investment intensity; R&D personnel ratio; proportion of internationally highly cited papers; PCT patent applications; IP trade balance; Nobel Prize count; and awards in major scientific fields (mathematics, physics, computer science, medicine, materials science) .

In addition to quantitative indicators, qualitative performance is equally important, including: world-leading scientific centers; major basic research facilities (world-class); original major scientific theoretical discoveries; leadership in international big science programs; key core technologies in critical fields; internationally influential scientific masters (a cohort); world-influential scientific journals (a group); world-class innovation R&D institutions (a batch in global top 100); world-class research universities (a batch in global top 100); internationally leading innovative backbone enterprises (a batch in global top 100); major manufacturing power in high-tech industries; well-designed innovation institutional frameworks; liberal and free innovation ecological environment; and innovation/creativity-oriented values.

5. Discussion and Recommendations

This study examines the quantitative and qualitative evaluation indicator systems for science and technology powers. Based on major international indicator systems and research reports on national innovation capacity and competitiveness, we analyze primarily from the scientific and technological dimension, 梳理 the main indicator systems, compare gaps between China and major powers based on key metrics, and propose indicator targets for joining the forefront of innovative countries and building a world science and technology power.

(1) This paper discusses and lists the main indicator systems for science and technology powers, including quantitative and qualitative indicators. Additional indicators could be proposed from different perspectives. We focus on quantitative indicators for horizontal comparison. Moreover, many qualitative indicators can be quantitatively analyzed, but arbitrarily assigning numerical values is not meaningful. What matters for joining the forefront of innovative countries and building a science and technology power are qualitative breakthroughs and substantial development in these areas.

(2) Building a science and technology power requires comprehensively advancing the innovation system as a systematic engineering project. Whether a country can join the forefront of innovative countries and become a science and technology power depends not only on the scientific and technological dimension but also on factors such as national size, population, economy, culture, education, politics, and business environment, all of which are interrelated. A glance at the basic research innovation capacity of Amer-

ica's world-class universities (as reflected by Nobel science prizes) makes it clear why the US is a science and technology power. World-class innovation education is essential. To achieve these goals, China must further reform its scientific and technological innovation system and mechanisms, improve the innovation system and layout, increase innovation policy supply, stimulate talent innovation vitality, continuously increase scientific and technological investment, and cultivate innovation-oriented social values and scientific culture. This paper analyzes only the narrow scientific and technological dimension, not because other aspects are unimportant, but precisely because they are decisively important and require specialized research.

(3) Steadily increasing R&D investment intensity is the most direct driving force for building a science and technology power. All science and technology powers prioritize S&T investment and maintain leading R&D intensities. Since the founding of the People's Republic, especially during the 40 years of reform and opening up and particularly since the Knowledge Innovation Program launched in the late 1990s, China's scientific and technological development has achieved remarkable accomplishments across broad fields and multiple levels, with some areas progressing from "catching up" to "running alongside" and a few achieving "leading" positions, making major contributions to economic and social development. A key reason for this progress has been recognizing the extreme strategic importance of scientific and technological innovation for national prosperity and continuously increasing investment. Although China's R&D intensity has risen from 0.90% in 2000 to 2.12% in 2017, significant structural problems remain compared with major powers: (1) R&D intensity remains low at around 2%, while advanced countries maintain 3% or higher; (2) The proportion of basic research in total R&D has long been around 5%, insufficient for long-term stable support of basic scientific innovation and resulting in inadequate S&T supply capacity; (3) Enterprise R&D intensity (enterprise R&D expenditure as a share of main business revenue) remains low, with insufficient vitality and initiative in corporate S&T innovation. Long-term, stable increases in S&T investment and adjustment of investment structures are the most critical measures for building a science and technology power.

(4) Strengthening basic research is a strategic choice for building a science and technology power. Basic research comprises experimental and theoretical work undertaken to acquire new knowledge of natural phenomena and observable facts without any particular application or use in view [26]. As Vannevar Bush stated in *Science: The Endless Frontier*, "Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn." Without basic research, technological innovation is water without a source or a tree without roots. All science and technology powers are strong in basic research and scientific innovation. Basic research requires

long-term scientific accumulation and is a lengthy, arduous exploration process. For a long time, China has mainly relied on original knowledge discovery from other countries, with few major original scientific discoveries that significantly contributed to human knowledge systems. Over the past century, science and technology awards, particularly Nobel science prizes, have represented major achievements in basic research—the brightest jewels in science's crown. China must make significant progress in these areas on its journey to becoming a science and technology power. To join the forefront of innovative countries and build a world science and technology power, China must become a powerhouse in basic research and scientific innovation. The nation needs strategic plans and policies to strengthen basic research, respect scientists' autonomy in selecting research directions and approaches, prospectively open new fields and directions for S&T innovation, and continuously invest in long-term basic frontier research. China should achieve scientific breakthroughs in major basic and interdisciplinary research fronts, produce a cohort of "Nobel-level" original major scientific achievements, contribute to enriching and constructing future human knowledge systems, and, more importantly, support the construction of a modernized powerful country.

(5) Focusing on creating and developing strategic technology industries is the fundamental support for building a science and technology power. A science and technology power must be a powerhouse in emerging technology industries and creation of new technology industries. While China cannot be world-class in all industrial fields, it must become world-class in strategic technology industries related to national security and economic lifelines; otherwise, it cannot be considered a science and technology power. While China has made tremendous progress, obvious gaps, shortcomings, and "chokepoint" issues remain in key core technology fields compared with powers like the United States. China must change the situation where key domain core technologies are controlled by others, vigorously promote breakthroughs in key common industrial technologies in critical areas, and truly master the initiative in competition and development. Only by mastering core key technologies can fundamental national economic security and defense security be ensured.

(6) China must strengthen its national strategic scientific and technological forces and optimize their layout, with forward-looking deployment in future strategic S&T fields. It is necessary to clarify the different functions and positioning of national strategic S&T forces in major basic research fields and major key core technology areas, carry out persistent exploration of major basic research and industrial common frontier core technology innovation, reduce administrative interference from short-term evaluations on long-term R&D, strive to transform from "catching up" to "running alongside" and even "leading" in more fields, and comprehensively achieve the transformation from "three modes coexisting, with catching up as the main mode" to "three modes coexisting, with running alongside and lead-

ing as the main modes."

A crucial but long-neglected reason for China's insufficient scientific and technological innovation is the lack of "innovation supremacy" social values throughout society. Our values and scientific culture are far from meeting the requirements for building a science and technology power. China must vigorously cultivate values that revere scientific spirit, create a liberal, free, and democratic scientific cultural environment, continuously liberate and stimulate talent creativity, and foster a social atmosphere that respects knowledge, respects talent, values innovation, and tolerates failure. Creating a favorable social environment for scientific and technological innovation development is a lengthy process.

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Note: Figure translations are in progress. See original paper for figures.