



FINANCE, COMPETITIVENESS & INNOVATION INSIGHT | FIRMS, ENTREPRENEURSHIP & INNOVATION

Promoting Innovation in China: Lessons from International Good Practice

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ABSTRACT

China considers innovation be one of the key drivers of its future growth and convergence with more developed countries. It spends more than 2.2 percent of GDP on R&D, above the average for the European Union, is a global leader in domestic patents, and has developed groundbreaking advances in key sectors such as high-speed trains, e-commerce and mobile payments. However, the quality of patents has been slower to improve, Chinese firms remain dependent on foreign suppliers in a number of core high-tech components, and resources do not flow easily to more productive firms resulting in large productivity gaps between market leaders and remaining enterprises. In order to restart its productivity engine and support continued technological catch-up, China must revise its approach to innovation policy. This paper takes stock of China's progress in building a modern national innovation (NIS) system, reviews international good practice in promoting innovation and shares policy recommendations to help China sustain its drive to become one of the global innovation champions.



INTRODUCTION

The growth of the Chinese economy is stabilizing around a “new normal”, with the government now attaching greater importance to the quality of growth than to its pace. To sustain this new growth path, productivity gains arising from technology adoption and innovation will need to displace investment as the principal driver of growth, and China will need to enhance the potential of its innovation system to fully leverage advances in technology. This paper assesses the country’s science, technology, and innovation capacity and research and development outputs, reviewing existing policies and identifying weaknesses. It then recommends measures that will aid China in its transition to an innovation- and productivity-led growth path by improving its national innovation system and by closing the distance to the technological frontier.

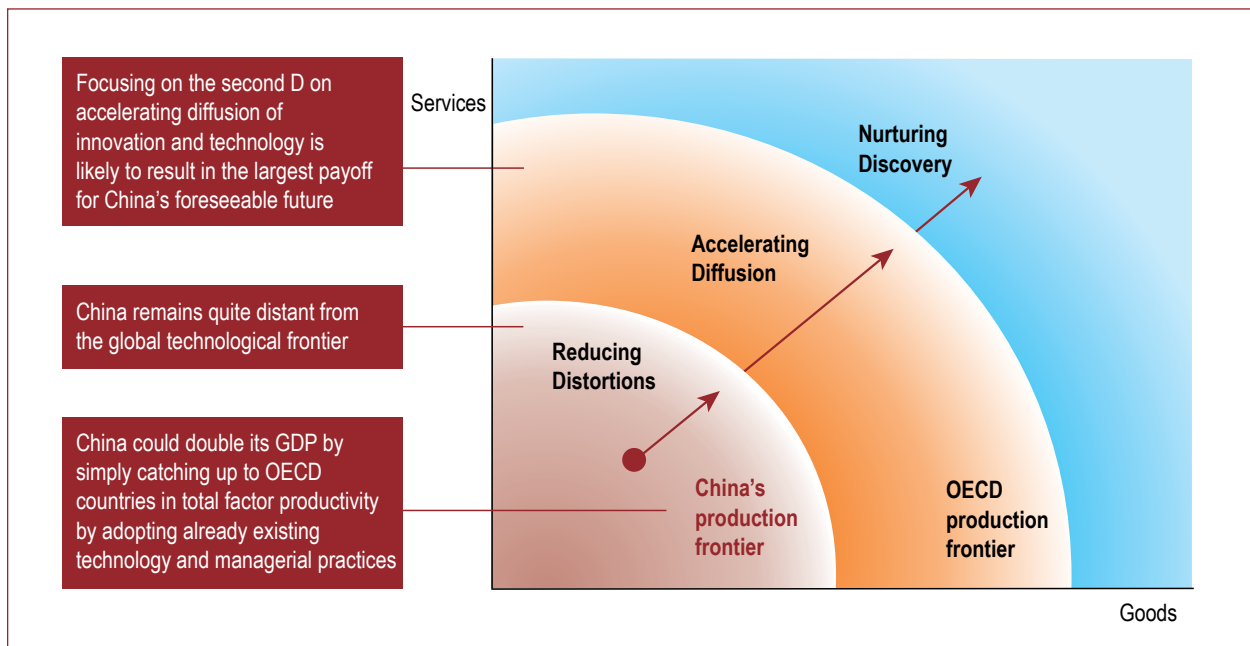
Many Chinese firms have caught up technologically by first linking with lead firms in global value chains and more recently through domestic applied research and technology acquisition via outward foreign direct investment. Leading Chinese firms have joined their foreign competitors as generators of knowledge by investing in scientific research and by mobilizing global talent. But the closing of technology gaps by industry leaders has not been enough to stem a decline in aggregate productivity growth and, despite ground-breaking advances in several key sectors, such as high-speed trains, e-commerce and mobile payments, China generally remains fairly distant from the global technological frontier. Annual total factor productivity (TFP) growth fell sharply from 2.7 percent in the early 2000s to only 1.1 percent in 2008–2017. TFP growth in manufacturing has nearly ground to a halt (DRC-World Bank 2019).

Restarting the productivity engine requires resolving challenges related to strengthening technology diffusion from leading firms to others, commercializing ideas, deepening managerial skills, creating an open innovation system, and building basic research capabilities. China has considerable scope for increasing productivity by i) eliminating market distortions that impede the sharing of best practices among domestic firms, ii) facilitating exit of poorly performing firms, and iii) closing some of the gap with the OECD production frontier by prioritizing the diffusion of existing technology and innovations (the so-called “technology absorption” strategy). And it can build the capabilities to extend

the global production frontier by nurturing the discovery and development of novel technologies (“frontier innovation”), as in figure 1.

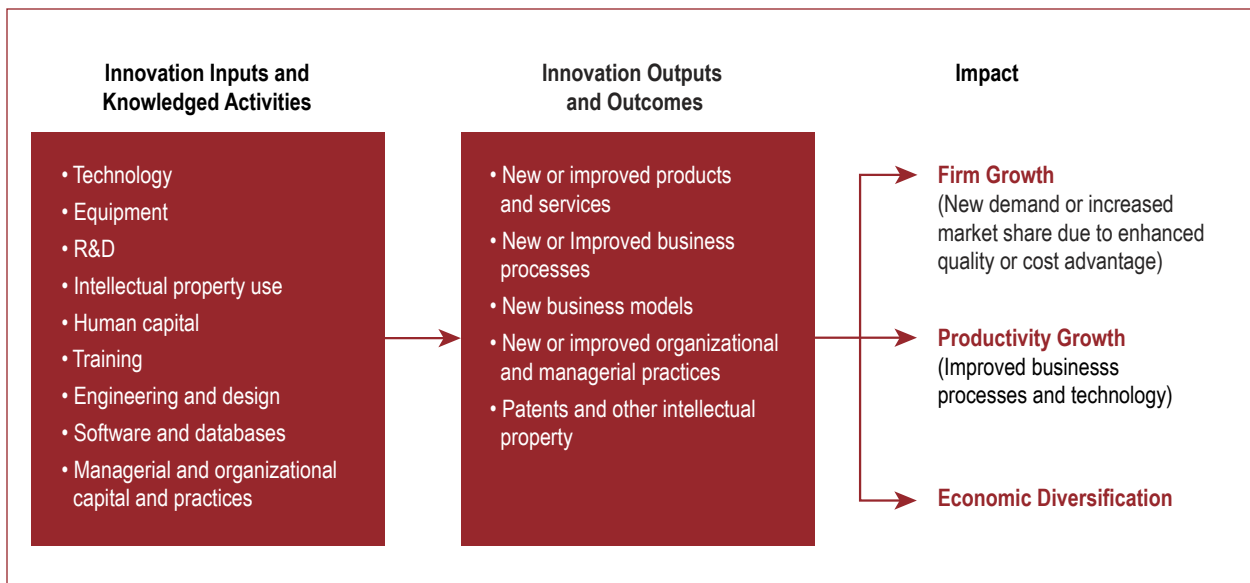
Chinese authorities have mobilized a wide range of policies to support improvements along the entire innovation “production function”, from inputs to outputs to outcomes (figure 2). The current emphasis of the authorities is on financial and supply-side support, with applied research and product development receiving primacy. Against the backdrop of continued rapid increases in China’s science, technology, and innovation (STI) expenditure, especially at the local level (whose share in total STI spending has already surpassed the central government’s), policy priorities may need to be reordered to respond to pressing needs not adequately addressed by the private sector. The key objective for China’s STI system should be to transition from quantity to quality in public spending. To achieve this shift, China ought to reform its STI system by enhancing government capabilities, balancing national and regional support for innovation, investing in basic research, leveraging open innovation, facilitating technology diffusion, and encouraging firms to improve their managerial practices. In addition, China would also be well-advised to continue to strengthen IPRs, promote a more bottom-up, market-based innovation policy, streamline innovation policies and expand the use of monitoring and evaluation in assessing the effectiveness and efficiency of public support for innovation

Figure 1: Reducing Distortions, Accelerating Diffusion, Nurturing Discovery



Source: DRC-World Bank 2019.

Figure 2: The Innovation “Production Function”



Source: Cirera and Maloney 2017.

POLICIES TO SUPPORT TECHNOLOGICAL PROGRESS IN ADVANCED ECONOMIES

Advances in technology have been increasingly driven by the growing ability of technologies to build upon each other. Electronic, telecom, digital, and biogenetic technologies are at the forefront of this process of mutual amplification.¹ In manufacturing circles, this change is known as “Industry 4.0”, and is characterized by robotics, artificial intelligence, and the industrial Internet of Things (IoT). Emerging technologies, including cloud storage and computing, have laid a foundation for generating, sharing, and applying data on a vast scale, permeating every corner of the economy and public management.

These advances have dramatically reduced entry costs for start-ups based on information and digital technology and increased the speed at which their services can be scaled-up. The internet and the global positioning system (GPS)—two “platforms of platforms”—have enabled the creation of firms such as Google, Facebook, Baidu, Tencent, Didi, and Mobike. Other technologies, including 5G mobile networks, are helping develop smart energy, transport, and urban infrastructure and more widely apply biomechanical, genomic, and robotic technologies in agriculture. Blockchain—a distributed digital ledger originally designed for accountancy of the digital currency Bitcoin²—is spreading beyond the financial and scientific domains to public service, digital identification, and supply chain management.

Green technologies ranging from photovoltaic and wind power supply, to next generation battery storage, to low-power information and communications technology (ICT) incorporated in “intelligent” manufacturing systems could, beyond spurring economic growth, reduce greenhouse gas emissions. They are reducing energy use and increasing the productivity of traditional industries. They are expanding environment-friendly services and clean industries like renewables, electric cars, and waste management. And they are stimulating the emergence of new, yet unknown, industries (World Bank, 2018). Advances in bio- and nanotechnologies also show promise in seeding new industrial activities.

In mature national innovation systems in developed countries, where the focus is on pushing the global knowledge frontier, emphasis has recently been placed on accelerating time-to-market and encouraging bottom-up innovation to better take advantage of emerging technologies. These policies help commercialize scientific and technological outcomes by fast-tracking innovation and accelerating patent review. In its *Horizon 2020*, the European Commission launched a pilot to fast-track market entry of innovative products and services. Reforms in the US sought to improve patent quality and shorten the approval process, including the milestone 2011 *America Invents Act*, which stipulates that after March 16, 2013 the First Inventor-to-File Rule would apply to all American patents. This replaces the long-prevailing First to Invent System.³ The Act, which aligns U.S. practice with that of all other countries,⁴ encourages individuals or firms with potentially lucrative inventions to not delay the patent filing, even if it is provisional, to avoid patent rights being awarded to a later inventor. It also establishes new mechanisms, such as a post-authorization review procedure to improve the quality of patents and safeguard the rights of inventors. To implement the new Act, the court identified the scope of patentability and guiding principles to reduce patent speculation and abuse of litigation opportunities. The U.S. Patent Office is striving to cut the average approval time from 35 months to 20 months and to bring the most valuable patented technologies to the market within 12 months.

European countries have identified technologies with large growth potential by leveraging the entrepreneurial drive of the private sector, working through discovery and experimentation. This sidesteps the problem created by weakening market and technology signals once countries operate close to the technological frontier. Such a bottom-up, innovation-based industrial policy has been called “smart specialization” (Foray, David and Hall, 2009; Foray, 2015). It prioritizes public support for innovation in economic activities that may not yet be fully “visible” but have the largest developmental, innovative, and spillover potentials. It relies on the “entrepreneurial discovery” to identify, select, and modify smart specializations and to provide public support based on the information from the markets. This process unites the private sector, academic bodies, and public administrations in an interactive process of mutual learning and knowledge sharing.⁴ It also strives to consolidate all knowledge in one place to reduce coordination failures and better guide private decisions.

A bottom-up approach also helps reduce the risk of capture of public innovation policies by incumbents, that is, companies and industries that already have a strong market position, rather than emerging firms that may still be too weak to affect public policy (and which may not reach the critical mass of development without public support). The public sector then concentrates public resources on the most promising activities and supports them at their critical junctures

of growth. Based on comprehensive and rigorous monitoring and evaluation, smart specialization helps governments support winners and cut off losers, much in line with Rodrik’s concept of what constitutes a good industrial policy (Rodrik, 2008).

For most EU countries, smart specialization underlies their regional and national innovation policies (World Bank, 2016). Its adoption is a condition for EU states to tap billions of euros from the EU’s Structural Funds in 2014–20. China may well find it useful to adopt such a bottom-up, market-oriented approach, as a complement to its current top-down policies. It could pilot this at a regional level and, depending upon results, roll it out across the country.

Other measures intensify the demand for business innovation. U.S. Federal Government departments use technology awards to encourage innovation. The “Grand Challenges” of the U.S. Defense Advanced Research Projects Agency (DARPA) offer competitors a prize if they can achieve a particular objective, such as perfecting a viable autonomous vehicle. Several EU countries (Ireland, for example) use public procurement to advance green growth objectives, incorporate innovative products in procurement criteria, conduct precompetitive procurement, and provide early markets for innovative products. Such procurement is a key driver of development and technological progress in architecture, health services, and public transport.⁵

CHINA'S PROGRESS IN BUILDING INNOVATION CAPACITY

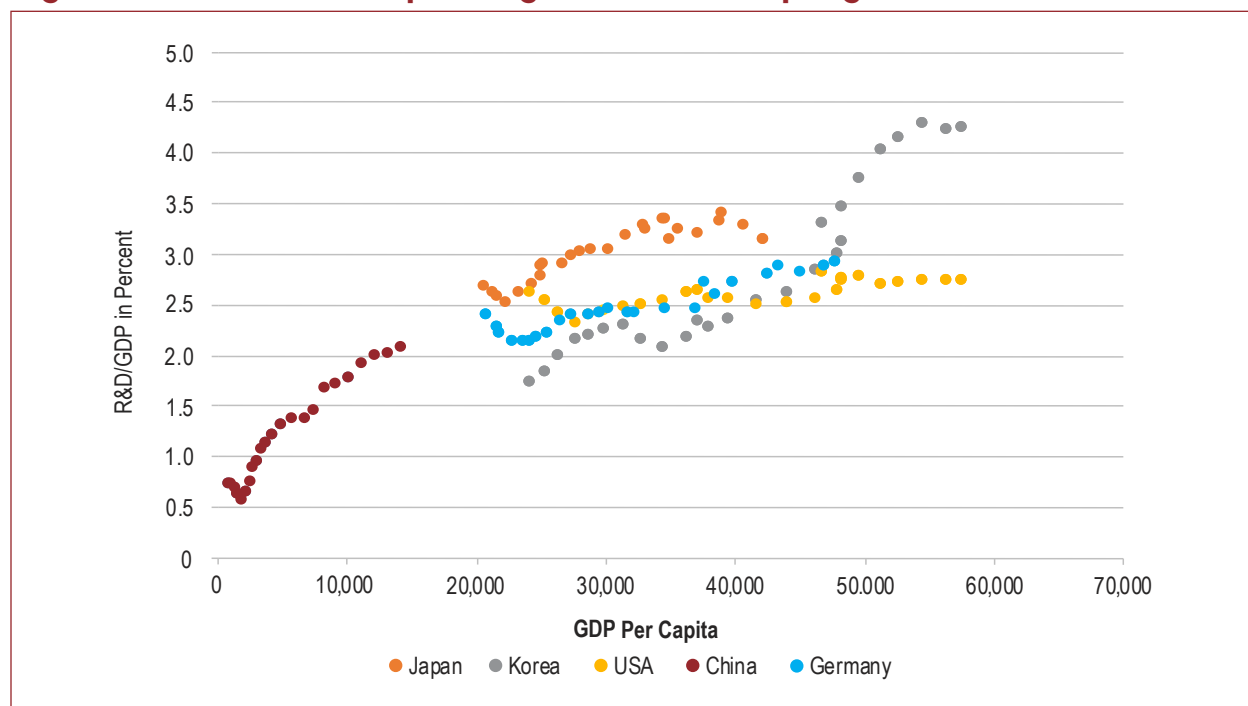
Although China has reached the world technology frontier in some areas (Alibaba, WeChat payments, high-speed trains) and is approaching it in others, a wide gap with major developed countries in core technical capacity remains. Within China, technological, productivity, and managerial capacity differences between leading players and the majority of Chinese firms are also large. The country thus needs to further strengthen its innovation capacity and enhance its innovation capabilities, using initiatives that have delivered results in advanced economies but which are adapted to the local context.

Innovation requires R&D spending, some on basic research but the bulk on downstream development and activities that produce marketable outcomes. A simplified linear view sees money going in at one end of the research pipeline, and research papers, patents, and innovative products and services emerging from the other, due to the efforts of an army of highly skilled workers aided by specialized measuring and testing equipment.⁶ This perspective appeals to planners, policymakers, and business managers, and there is empirical support for the belief that returns to R&D can be quite high if supported by a conducive environment.⁷ Scientific papers and patents can begin pouring out quite rapidly, as China shows.⁸

But it is also apparent from the faltering productivity performance of industry and of research⁹ in some western countries and in China, that a linear strategy with its emphasis on R&D spending and on a few metrics is unlikely to yield sustained productivity gains.¹⁰ A review of five prominent Chinese industries finds that Chinese firms “rely on their low-cost advantage and mass production mode as their main competitive advantage instead of product innovation and product and service quality” (Cooke, 2018). A more comprehensive, multifaceted strategy is therefore warranted, one that balances a strong emphasis on measures that improve management skills at the firm level—and that accelerate the diffusion of technology and the commercialization of innovations—with the basic research that leads to scientific discovery.¹¹

While a strong performer in some inputs (R&D spending) and outputs (patents), China falls short of leading economies across a range of other important inputs. Despite much recent progress, China lags in high-quality human capital (measured by R&D professionals, PhD students, and tertiary enrollments relative to the country's population), internet access and use, and the overall business and regulatory environment. Chinese firms also need to strengthen management quality to catch up with practices in frontier countries. Findings from the World Management Survey (WMS) suggest that Chinese managers excel at meeting short-term production targets and at competing based on price, but among 40 countries surveyed, they are among the less sophisticated in innovation-related practices, such as long-term strategic planning and staffing.¹² Chinese firms' managerial capabilities are therefore weaker than the sample's average, with China located between Greece and Turkey (Bloom, Sadun and Van Reenen (2017); Cirera and Maloney 2017). While the worst managed Chinese companies are only slightly worse than their U.S. counterparts, the difference between the top Chinese and U.S. firms in the quality of managerial practices is much larger (DRC-World Bank 2019). This suggests that there is much room for improving managerial practices across the whole spectrum of firms, with the payoff greatest when upgrading the management of leading Chinese firms.

Figure 3: China's R&D Spending has Grown Rapidly, 1995-2017



Source: DRC-World Bank 2019.

China's Spending on its National Innovation System

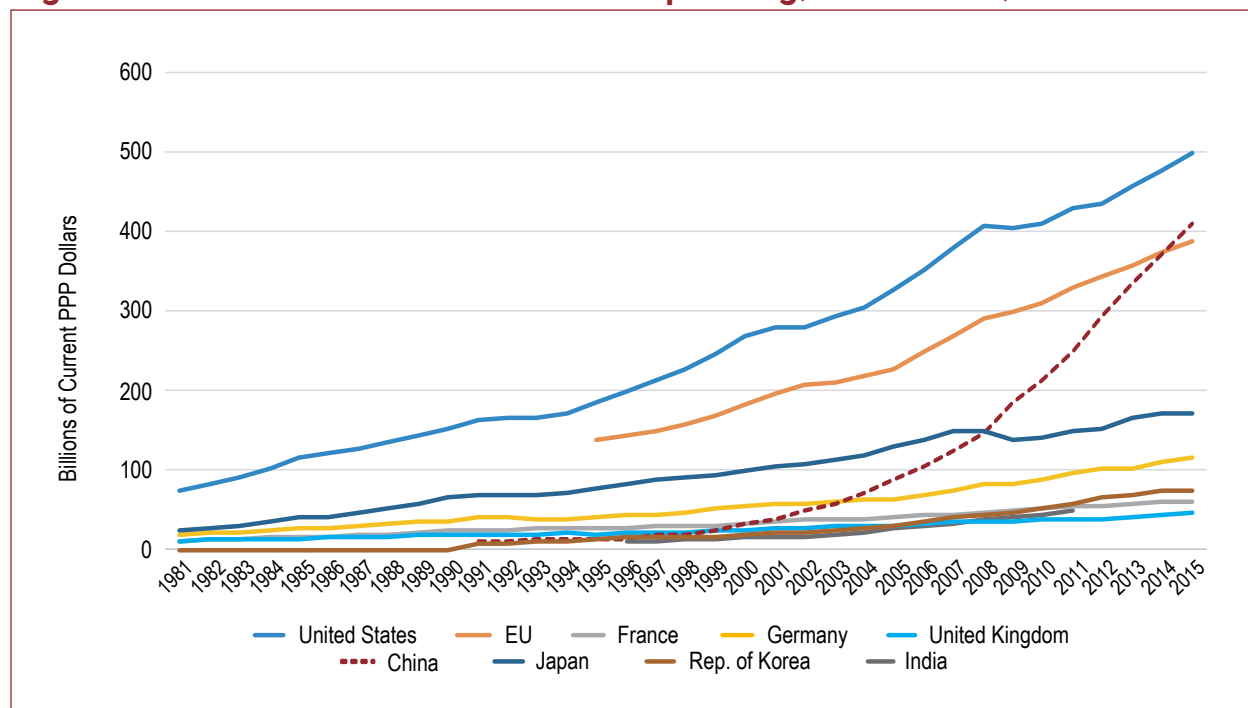
China has a comprehensive national innovation system (NIS), building on policies introduced in the early 1990s. In addition to the central ministries and specialized agencies there are many more innovation-oriented institutions and agencies at regional and local levels. There is also a well-developed system of incubators and high-tech and science and technology parks, estimated to exceed 3,000 in number.¹³ In 2015, there were 146 national high-tech parks, which housed companies responsible for one-third of R&D enterprise spending in the country (OECD, 2017).

STI spending grew from RMB 5 trillion in 2007 to RMB 18.7 trillion in 2016, but recently slipped as a share of total public spending (China, Annals of Science and Technology, 2017). Spending on R&D alone amounted to 2.13 percent of GDP in 2017, a little below the OECD average, which was 2.37 in 2017 but higher than expected given China's per capita income (figure 3).

In absolute numbers, China's R&D spending (in purchasing power parity (PPP) terms) is now second only to that of the United States (figure 4) and was estimated to account for about 20 percent of global R&D outlays in 2017. The rate of growth is higher than in the EU and the United States, suggesting that China's share in global R&D spending will continue to rise. Reaching the R&D target of 2.5 percent of GDP by 2020 or so would increase China's share in global R&D spending to about one-fourth.¹⁴ The United States and China alone would then account for more than half the world's R&D spending.

National and regional R&D spending has risen rapidly, with regions now spending more than half of the total (Science and Technology Annals, 2018). Even though all provinces promote R&D and encourage patenting by setting quotas and offering incentives to maximize filings, the disparities among regions are wide on R&D intensity and patent filings—coastal regions dominate (Sun et al, 2015). That would be in line with the same patterns in advanced countries, where innovation activity is

Figure 4: China's Share in Global R&D Spending, 1981-2015, PPP



Source: Authors based on National Science Board (2018)¹⁵

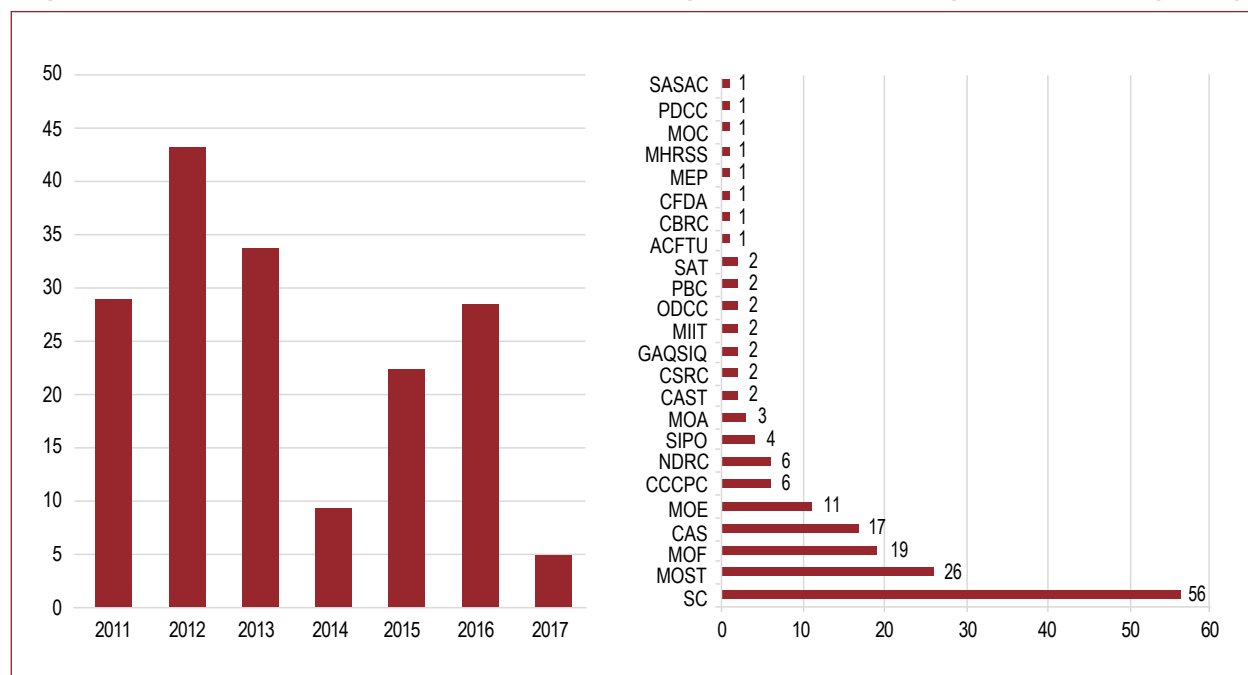
Note: Foreign currencies converted to current dollars through PPP.

concentrated in a few regions, such as Silicon Valley in the United States, Emilia Romagna in Italy, and Baden-Württemberg in Germany.

Most national and provincial public funding in China is directed to a few strategic industries, selected by the national and regional governments as part of their top-down innovation strategy. In 2015, rail and other transport equipment received more than one-fourth of all public support for innovation, followed by computers (17 percent) and general-purpose machinery (7 percent) (OECD, 2017). Unlike the vast majority of other middle-income and even some high-income countries, China's enterprise sector accounts for three-fourths of total R&D spending (DRC-World Bank, 2019). While this share is above the vast majority of other middle-income economies as well as the OECD average of two-thirds, as much as one-third of the total in 2015 was due to R&D outlays of SOEs (down from 55 percent in 2005) (Molnar, 2017).

There is ongoing debate about the overall returns to China's R&D. During 2006–10, returns were relatively low, seemingly due to a lack of complementary factors such as quality of scientific infrastructure, overall functioning of the NIS, and firms' capabilities (Goni and Maloney, 2017). But there is also evidence that private spending has boosted output and productivity. One study estimated that, among 12,000 Chinese firms in 120 cities during 2002–04, firm output increased by around RMB 0.4 for each additional RMB 1 spent on R&D in the previous year, similar to Japan and the United States in the 1970s (Goh, Li and Lixin, 2015). Although there is much evidence of public policy supporting several successful technologies (such as high-speed trains), the overall efficiency of public spending is mixed (Liu et al, 2017). This is likely because public support seems to “be strongly biased in favor of SOEs, especially those owned by local governments” even though “private sector firms exhibit a higher rate of innovation per renminbi invested in R&D than SOEs” (Wei, Zhuan and Zhang, 2017).

Figure 5: Distribution of Innovation Policy Instruments by Year and Agency



Source: Authors' calculations based on data collected by Ruimin Pei and Hua Shen.

China's Innovation Policies

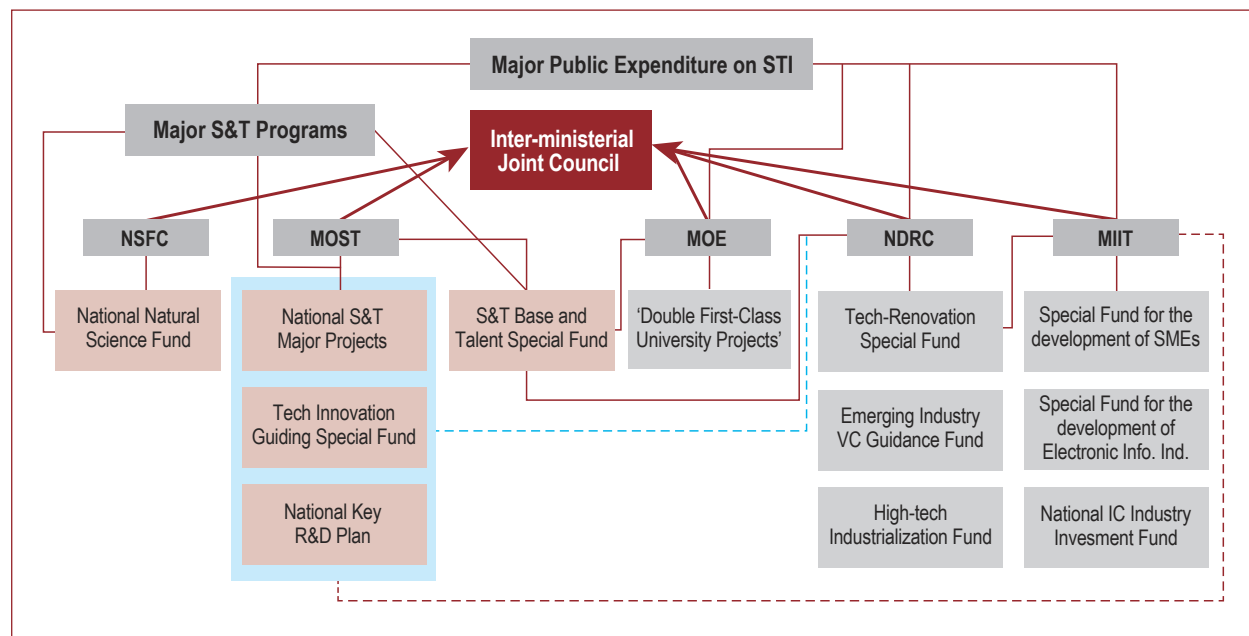
China's top-down approach to innovation policy dates to the launch of the Medium and Long Term Plan (MLP) in the mid-2000s to "re-conceptualize the broader innovation policy framework", "introduce the theme of indigenous innovation", create a Leadership Small Group to guide and coordinate technology development, and make it clear that implementation would be "with key point projects and key point tasks". The MLP committed China to achieve four broad objectives by 2020: to allocate 2.5 percent of GDP to R&D, to source 60 percent of growth from the "contribution of S&T progress", to base 70 percent of production on homegrown technologies, and to raise the share of strategic and emerging industries to 15 percent of GDP (Ling and Naughton, 2016).

To further these objectives, more than 170 policies supporting STI have been introduced since 2011.¹⁶ They span socioeconomic objectives (productivity, diversification, human capital, entrepreneurship, and inclusion) and STI objectives (research excellence,

technology transfer, and R&D and non-R&D innovation). And they use a wide range of instruments: fiscal incentives, grants, loan guarantees, vouchers, equity, public procurement, technology extension services, incubators, accelerators, competitive grants and prizes, science and technology parks, and collaboration and networks (many of these instruments are highlighted later in this chapter).

The number of instruments per period reflects the five-year plan cycles, with most toward the front end of each cycle (figure 5, left panel). The instruments in the policy mix are spread across 24 government entities, 16 of which implement between 1 and 3 instruments each (figure 5, right panel). A full one-third of the number of instruments are implemented by the State Council, more than twice the proportion of instruments of the next entity, the Ministry of Science and Technology (MOST). The State Council is therefore critical to overall implementation of the policy mix, though the number of policies does not necessarily mesh with budget allocations (data are not available on the public resources allocated to each policy).

Figure 6: Institutional Structure of Central Government Spending on Innovation



Source: DRC-World Bank, 2019.

The large number of entities with only one, two, or three instruments raises the question of integration of their interventions into the overall innovation policy. Despite the recent reform of the public R&D support system, which helped streamline STI spending by strengthening the role of MOST in managing the flows of public R&D, some researchers argue that coordination of policies could be strengthened and the overlap among R&D programs could be significantly reduced (Liu et al., 2017). Moreover, the budget allocation system is multitiered and confusing because instruments and budgets are ascribed to one entity at the general level but the action plans may be carried out by other agencies.

Spending by ministry indicate that the responsibility for implementing R&D policy rests largely with five agencies: MOST, the National Development and Reform Commission (NDRC), the National Science Foundation of China (NSFC), the Ministry of Industry and Information Technology (MIIT), and the Ministry of Economy (MOE) (figure 6). Together, they account for almost one-third of total public R&D spending.¹⁷

Basic research is mostly funded through the NSFC and the China Academy of Sciences (CAS). Both saw their budgets more than double between 2011 and 2017 to more than RMB 30 billion. Overall outlays on basic research increased to about 5.3 percent of total spending, with further spending increases envisaged.¹⁸ Spending on applied research, mainly funded through MOST, MIIT, and CAS, has also increased.¹⁹

Policy instruments seem to favor financial instruments over regulatory, advisory, and other types of support.²⁰ Such emphasis suggests that the main market failure that the authorities seek to address has to do with funding and access to finance. Tax incentives, matching grants, and funding for collaborative activities cover twice the number of instruments of the next four: i) business advisory and technology extension services, ii) science parks, iii) incubators and accelerators, and iv) quality infrastructure and standards for innovation.²¹ In addition, the authorities provide substantial financial support through more than 2,000 government-guided funds and a plethora of venture capital and private equity funds co-funded by central and local governments.

Supply-side interventions seem to dominate support instruments on the demand side (in terms of the number of instruments, not the allocated budgets), and instruments that aid applied research outnumber support to basic research by a factor of 2 to 1. Most policies are targeted at young firms (pre-seed, seed, and start-up) and micro and small firms. Of 42 instruments devoted to businesses along some stage of their life cycle, 36 are focused on seed funding or the start-up phase, while scaling up and mature stages are the objective of only three instruments each. This pattern is consistent with diversification, one of the main economic objectives of Chinese innovation policy given the sharp decline in the contribution of new entrants to firm-level productivity growth in China (DRC-World Bank, 2019). But the imbalance discriminates against potential “gazelle” firms, which need to scale up, undertake organizational and process innovations, and connect to a larger network of suppliers and customers.²² It also goes against the experience of countries like Japan or South Korea, which supplemented financing support for firms with programs focused on building of firm innovation capabilities (Lee, 2016 and Malerba, 2006).

The volume of the government’s support for business R&D is close to the OECD median, but is much higher than what China’s level of income would suggest. Tax incentives represent about half of the value of the total support (OECD, 2017 “R&D Tax Incentive Indicators, March). There is evidence that tax incentives promote private R&D spending in China: a 10% reduction in R&D user costs tends to boost R&D spending by about 4 percent in the near term. This is a large impact, but it nevertheless remains lower than in developed countries, likely reflecting a less developed institutional environment that dampens the size of the returns (Jia and Ma, 2017). The impact of tax incentives is also higher among private firms than among private firms with “political connections” and among SOEs. The latter seem to invest in R&D regardless of tax incentives. This suggests that there is scope for further increasing the efficiency of tax support for private R&D by focusing it on the private sector.

Further inquiry would be needed to determine whether tax incentives and direct support policies are addressing the constraints inhibiting high-productivity entrants. Such inquiry should be based on (currently unavailable) data on the budget allocations for each support instrument, which would provide information for policymakers to determine whether the policy mix is appropriate for the needs of national and local innovation systems. Most developed countries provide such data as a matter of course to adjust their innovation policy mix. China could take steps in this direction.

Also important is analyzing the efficiency of public support for innovation, which is rarely, if ever, monitored and evaluated for impact. Policies thus proliferate and are hardly ever discontinued. In addition, public support seems to channel a significant part of funding to SOEs. In 2013, public funding represented 9 percent of total intramural R&D spending among SOEs, three times more than among private enterprises (Liu et al, 2017). It suggests a strong preference for SOEs even though innovative outputs among state firms seem to be generally lower than among private firms, examples of several innovative SOEs notwithstanding (box 1).²³ Innovation policy instruments also emphasize potential innovators over non-innovators, who do not appear to be the focus of any instruments, even though this group may face the greatest barriers to innovation.

Industry distribution of public support for innovation in China is quite concentrated. Railways and transport equipment, mostly high-speed train technology, received more than one-fourth of total innovation support in 2015. The top five recipients—railways and transport equipment, computers and electronic, general purpose machinery, special purpose machinery, and electrical machinery—were responsible for almost two-thirds of total support (OECD, 2017). In most developed countries, public support for innovation across industries is spread more equally, suggesting a larger role for market-driven mechanisms.

Box 1: Innovative SOEs in China

Over the past decade, Chinese SOEs have developed multiple innovations, including breakthroughs in introducing new technologies and industry standards, building new markets, and developing new business models. Such breakthroughs have likely had substantial positive spillovers on the rest of the economy and helped support productivity growth in the private sector.

The most innovative SOEs include CRRC, a producer of widely acclaimed high-speed trains; SGCC, manufacturer of ultra-high voltage transmission technology and smart grid innovation; COMAC, producer of new commercial aircraft, which promises to break the global duopoly of Airbus and Boeing; CASTC, developer of the Beidou Navigation Satellite System; Sugon/Dawning, the leader in high speed computing; and ZTE, one of the emerging global leaders in communications, including 5G networking and optical access technology. ZTE spends 12.2 percent of its revenue on R&D, almost on par with China's leading private firms such as Alibaba or Baidu, suggesting that public ownership does not always mean less innovation.

Source: Authors' own.

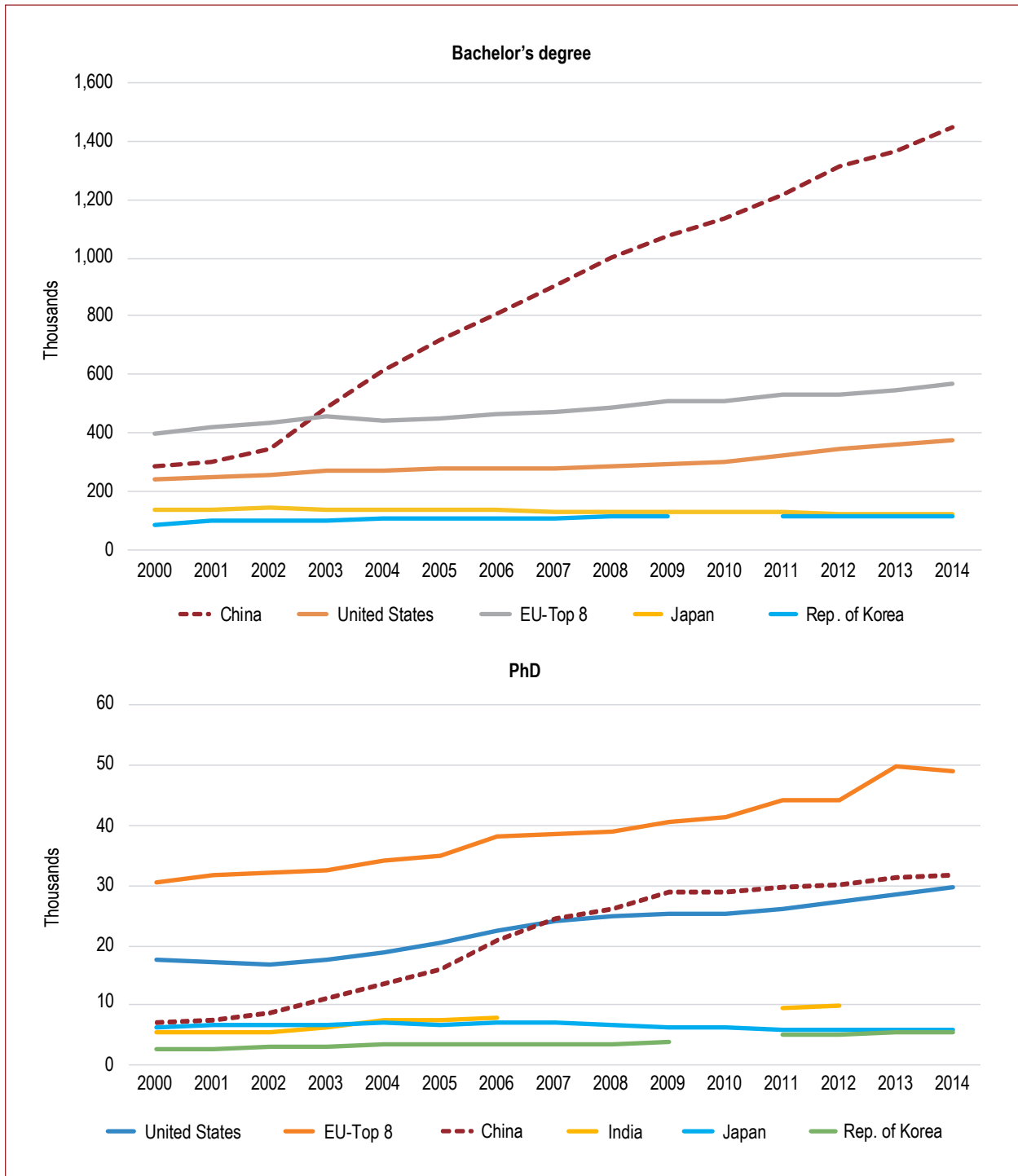
Research Capacity

Complementing the large and growing R&D spending has been investment in training students in science and engineering (S&E), who represented around half of all bachelor degrees. In 2014, S&E graduates comprised a group of almost 1.5 million people—more than the combined total of degrees in S&E awarded in the United States and the EU-8 (figure 7).²⁴ In addition, more than 30,000 received doctorates in S&E disciplines, more than in the United States and three times more than in India.²⁵ The number of graduates and scientists has since increased further, especially as the data do not include the thousands of Chinese students receiving advanced training abroad, at least half of whom return to China attracted by the Thousand Talents and similar programs introduced in the early 2000s to encourage the return of members of China's scientific diaspora.²⁶

Thanks to the large annual inflow, the pool of researchers climbed from 443 per million people in 1996 to 1,113 per million in 2014, still well below 3,122 in the United States and 4,947 in Japan. However, China still has only two researchers per 1,000 employed, well below 10 in the EU and the United States, 14 in Korea, and almost 18 in Israel (OECD, 2017).

Training in western and Japanese research institutions and the connections forged there have contributed greatly to the quality of China's research capital.²⁷ China strongly encourages researchers to publish in refereed scientific publications, and urges researchers and firms to patent their findings. It is now second only to the United States in number of publications. The quality of papers—initially a weakness—is improving,²⁸ apparent from the scoring of scientists by the Nature Index, which shows that the Weighted Fractional Index (WFC) for Chinese researchers has risen and only the United States continues to outrank China.²⁹ Forty Chinese institutions were among the top 100 institutions worldwide that registered the greatest increase in their WFC scores between 2012 and 2015. The United States was second, with 11 (Nature, 2016). Chinese researchers are engaged in cutting-edge research on stem cells, genomics, protein and green chemistry, optoelectronics, supercomputing, machine learning, ballistic and anti-satellite weaponry, and other areas, but citation counts suggest that the strengths of Chinese researchers are greater in physical than biological sciences. China's progress is all the more impressive given the state of the country's teaching and research institutions in the early 1980s, and some continuing challenges.³⁰

Figure 7: Bachelor and PhD Degrees in Science and Engineering are Climbing Rapidly, 2000–14



Note: The Top 8 EU total includes aggregated data for the eight EU countries with the highest number of S&E bachelor and doctoral degrees awarded in 2014.

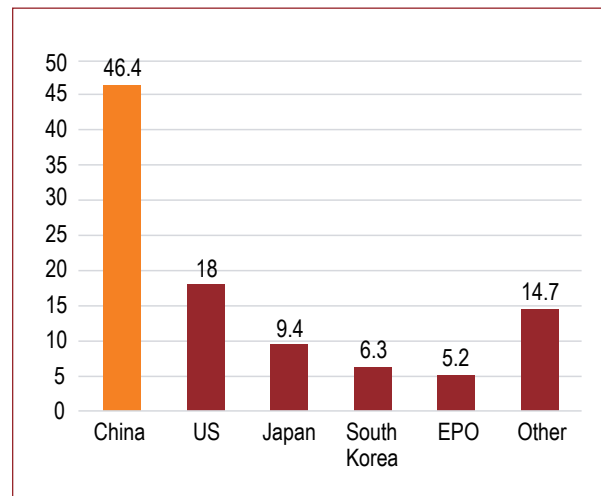
Source: Authors' own based on the National Science Foundation Science and Engineering Indicators 2018.³¹

Improvements in human capital and rapid growth in STI spending have led to a boom in invention and utility-patent applications, especially after 2008. By 2011, China led the world in the number of domestic patents filed.³² In 2018, China’s National Intellectual Property Administration received 1.54 million patent applications, which accounted for almost half of the world’s total and almost three times more than the United States (figure 8).

The number of international patent submissions has also increased, as reflected in the growing number of patent submissions to the U.S. Patent and Trademark Office (PTO) and the European and Japanese patent offices. Patents granted to foreign parties by the U.S. PTO increased from 111,823 in 2010 to 178,184 in 2018, with applicants from China receiving 2,655 in 2010 and 16,759 in 2018—a steep increase (USPTO, 2018). The quality of patents has also gone up.³³ In utility patent applications, China is now the fifth most patent-intensive country. Chinese international patent applications (PCT) counted by the World Intellectual Property Organization (WIPO) have also surged: China has now overtaken Japan as the second-largest source country of patent applications and is likely to overtake the United States in 2020 or so.³⁴

The quality of patents merits further improvement. Despite the surge in patenting and heavy spending by enterprises, only a small proportion of Chinese patents are registered abroad at the patent offices in the United States, EU, and Japan, implying their lower quality (Molnad, 2017). 96 percent of patents are filed only in China and two-thirds of China’s most research-intensive companies file no patents abroad. Moreover, the number of triadic patent filings is miniscule (Boeing and Mueller, 2019). Forward citations received by patents abroad and claims on Chinese-owned patents are fewer than those of the leading industrial economies, as is the percentage of national patent stock that represents truly sophisticated technologies (Prud’homme and Song, 2016, Prud’homme and Zhang, 2017). Most patents are also concentrated in few cities, including Beijing, Shanghai and Shenzhen (Branstetter, Glennon and Jensen, 2018), and few patents are the

Figure 8: Patent Applications in Percent of the World’s Total, 2018



Source: Author’s own based on WIPO 2019.

Note: EPO is European Patent Office.

result of interfirm or business–science collaboration. Most R&D projects reside within individual firms, with little input from universities or other firms (OECD, 2017). Foreign-owned entities are a small source of invention patents but receive more one-third of the patents granted (DRC-World Bank, 2019).

China’s renewable energy industry leads other countries in patent applications but only 1.4 percent are submitted to overseas patenting offices. The citation rate for China’s photovoltaic (PV) patents is a low 14.9 percent against more than 60 percent for PV patents received by firms from Germany, Japan, and the United States. Chinese firms are the leading global manufacturers of wind turbines (with five firms in the top 10 in 2015).³⁵ But they have received very few international product or process patents for new technologies, indicating that innovations were modest and incremental (World Bank, 2018). Uneven patent quality may be one reason there is so little impact of increased patenting on productivity (OECD, 2017). Low patent quality can become self-reinforcing as firms attempt to use them to create barriers to entry for competitors, especially start-ups—blocking freedom to operate and increasing transaction costs

associated with “identifying and invalidating low-quality patent rights, licensing them, or subjecting them to lawsuits” (Prud’homme and Zhang, 2017).

Even with these concerns, however, China’s patents are making an important contribution to economic growth. According to one estimate, higher patent density is associated with an increase in the productivity of firms (Zhao and Liu 2011; Li, 2012). Another estimate shows that a one-standard-deviation increase in patent density is associated with a 6-percentage point higher city GDP growth in a subsequent period (Sun et al, 2017). The effect is particularly strong for inland areas, suggesting patenting that promotes productivity could, in principle, enable lagging inland regions to narrow the gap with the more advanced coastal zones (Sun et al., 2017; Xu et al., 2017). And while neither SOE presence nor college student density appears to have a direct effect on city-level growth, cities with higher college density and a more supportive local government tend to produce more patents per capita (Sun et al., 2017). Lower SOE presence appears to be associated with better performance on overall patent and trademark density, but a greater SOE share is positively and significantly related to invention patent density. This topic deserves to be validated by more research as it could help shape regional policy.

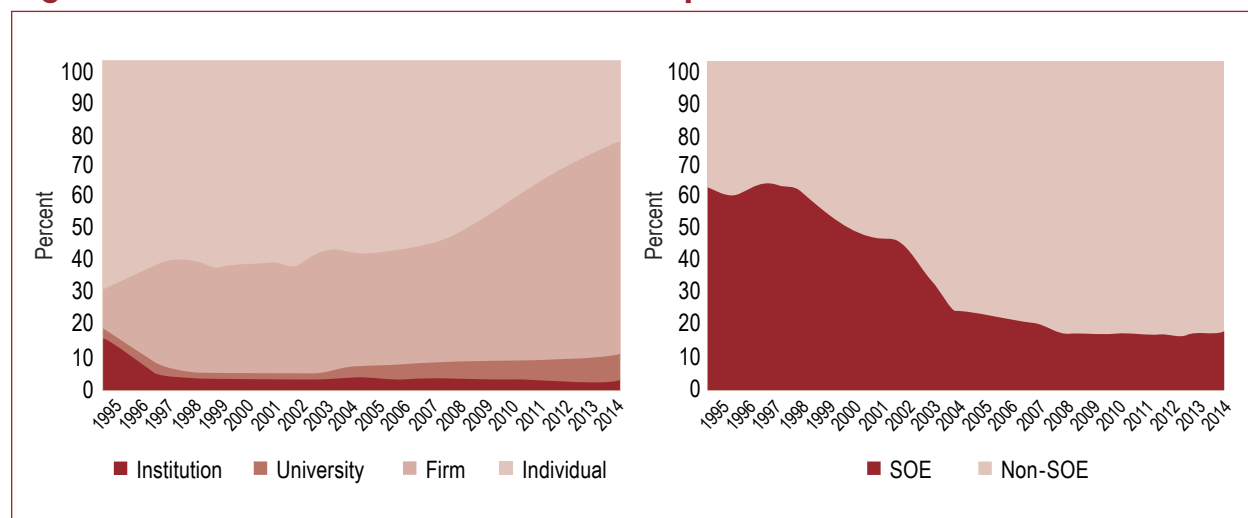
Although China’s investments in innovation have intensified and patents have proliferated, TFP growth has trended down since the turn of the century and stagnated since 2012 (Wu, 2016). This may stem in part from the dominance of utility models of questionable value and lower-quality patents not derived from formal employment contracts.³⁶ Another concern is that, even though firms rather than institutions or universities have become the most important source of patents in China over the last two decades (figure 9, left panel), most patents are produced by just a handful of companies. To facilitate greater rates of technology transfer and adoption in industries, there is ample room for tightening university-industry-research collaboration and firm-level collaboration.³⁷ Only 9 percent of all Chinese firms had any

patents, and among these firms only 5.8 percent had multiple patents, representing a remarkable 91 percent of all patents (Fang, He and Li, 2016). The computer industry had the highest number of patents per firm, 20 times more than the food industry, while the medicine industry had the highest ratio of firms with patents. Younger mid-sized firms, larger firms, and firms with more R&D spending tend in general to patent more, and exporting firms patent more than nonexporting firms. The share of patents attributable to SOEs has declined substantially since the mid-1990s (figure 9, right panel), even though SOEs are more heavily subsidized than private and foreign firms. This may indicate that SOEs are less efficient in using their R&D budgets, or that many SOEs are in industries with low R&D intensity (Wei, Xie and Zhang, 2017; Boeing, Mueller, and Sandner 2016).

There are concerns about how China’s intellectual property rights (IPR) regime affects the volume and quality of patents, given evidence indicating the significant positive effects of stronger IPR protection on innovation and corporate R&D in China (Fang, Lerner, and Wu 2016; Lin, Lin, and Song 2010). Despite recent improvements in IPR laws, policies, patent evaluation,³⁸ quality thresholds for utility patents,³⁹ and enforcement, more progress is needed. MNCs and local firms continue to complain about IPR breaches and the difficulty of enforcing claims given the complexity of the IP system, the pressure to transfer technology, the protection afforded to Chinese firms, and the limited deterrence value of the statutory damages awarded (OECD, 2017).

China’s first-to-file system, which does not recognize trademarks registered in other countries, encourages trademark “squatting” by local firms, which is damaging for foreign companies. Other problems arise from gaps in regulations (as in China’s import-export regulations, the law governing science and technological progress, and regulations governing standards involving patents) and in other IP laws (China has, for example, yet to accede to the UN’s 1991 convention on protection of new varieties of plants) (Prud’homme 2012; Zhang

Figure 9: Firms Have Become the Most Important Source of Patents in China



Source: Authors' own based on the National Bureau Statistics of China.

et al. 2017). Agencies and courts administering IP continue to suffer from capability constraints, and coordination across some central and state-level bodies could be improved. Two-thirds of Chinese firms believe that patents do not provide enough protection against IPR infringement (OECD, 2017). Smaller, private companies are often most affected, because they tend to lack the power and expertise that large firms and MNCs possess for fighting violations.

Technology Upgrading and Diffusion

Chinese firms have made major progress towards upgrading their technological capacity through diffusion of technology from the rest of the world and, more recently, through their own advances.⁴⁰ In manufacturing, Chinese firms have demonstrated the ability to reverse engineer, adapt, and improve foreign production technologies and to scale up their production at short notice. This narrowed China's estimated hypothetical output per worker using U.S. technology and actual output from 7.79 in 1979 to 3.86 in 2008 (Shen, Wang, and Whalley 2016). Chinese companies have made significant breakthroughs in technological research and industrial development of high-performance computers, Internet applications, new generation

broadband mobile communications, the next-generation Internet, and quantum computing. The R&D intensity and market competitiveness of Huawei, ZTE, Alibaba, Baidu, and Tencent have made China a dominant force in developing international standards for 4G mobile telephony. Chinese companies are also among the global leaders in the development of the 5G mobile standard. China's application software and support platforms have reached an internationally advanced level. Patents in electrical machinery, computers, and digital communications are among the top three technology fields for the Chinese patent office.⁴¹

As a result of this continued progress, the composition of Chinese exports has rapidly shifted toward more skill-intensive industries (Amiti and Freund, 2010) and its export mix increasingly overlaps with that of developed countries, even if they are concentrated at the bottom of the price-quality range.⁴² These outcomes have been supported, at least in part, by Chinese firms acquiring advanced technology and moving up the product value chain. In China, technological catch-up has been more prevalent in locations with greater industrial diversity (Zhang, 2015), in sectors with lower prevalence of SOEs (Guan and Pang, 2017), and among exporters and foreign-

owned firms (Olabisi, 2017). Firm performance has also been aided by the internet, even in the pre-Alibaba era, facilitating communication with buyers and input suppliers (Fernandes et al., 2017).

Access to foreign inputs—a significant driver of productivity growth in many countries—has been important in facilitating technology adoption at firm level. Lowered import tariffs in China made higher-quality imported intermediates attractive for more firms, raised domestic product quality, and stimulated incremental innovation (Fan, Li, and Yeaple 2015).⁴³ Indeed, imports of capital goods are a known channel for foreign technology transfers, R&D spillovers, and product upgrading (Eaton and Kortum, 2001).

Despite rapid progress in developing in-house technological capacity, industries such as integrated circuits, high-precision sensors, basic software, large-scale industrial software, and biotechnology continue to require high levels of integration with producers elsewhere in the world. And foreign producers have 80 percent of the market for industrial robots, advanced automatic control systems, computer numerical control machine tools, and computer numerical control systems. Chinese companies also depend on foreign suppliers for three core components—controllers, servomotors, and reducers (Peng and Dongyu, 2015). Of four major technologies—computation, visualization, voice recognition, and driving systems—Chinese enterprises lead only in voice recognition. Key targets for drug R&D, cell lines for vaccine antibody production, and critical genes for animal and plant breeding are largely monopolized by developed countries. In the development of new materials, China's overall technical level in basic raw materials is not high. And its consumption of material and energy per unit of GDP is well above the average for industrialized countries, in part because it lacks process technology know-how and is weak in supporting and engineering capabilities.

China's Indicator—Based Innovation Rankings

China has reached—or is approaching—the global technology frontier in some areas. But its comparative advantage still resides mainly in low-cost and large-scale manufacturing. A wide gap in core technical capacity remains with the major developed countries.

Several innovation indexes that rank countries suggest that China is moving up the ladder, but still has some way to go. Increased spending has strengthened STI capacity, but acquiring innovation capability comparable to some of China's neighbors and western countries could take longer.

China's performance varies widely on innovation rankings: The Bloomberg index of innovative economies ranks China in 15th place, the top place for a non-high-income economy. China scores highly on patent activity (2nd) and tertiary efficiency (5th), while it lags behind in productivity (47th) and researcher concentration (39th).⁴⁴ The WIPO/INSEAD/Cornell Global Innovation Index 2019 shows that China moved from 17th to 14th place worldwide and is now the only upper-middle-income country in the global top 30 (WIPO/INSEAD/Cornell, 2019). Other rankings show similar results.

On balance, these assessments reinforce the perception that, except in a few sectors such as the digital industry, China's innovation capabilities and underlying learning and creative culture may yet take some time to mature fully.⁴⁵ The differences across indexes are also driven by varying methodologies, choice of indicator, and areas of focus. Some emphasize quantitative indicators and areas where China has been a strong performer. Others give greater weight to governance, financial, political, business, and regulatory environments and to ecological sustainability—areas where China performs less well than comparator countries. Still others downplay China's strengths by ignoring factors important for innovation, such as availability of venture capital, strength of manufacturing, penetration of consumer ICT technologies, and size of the domestic market, where China has an advantage over countries ranked higher.

INNOVATION REFORM AGENDA

China seems to have already achieved tangible success in supporting innovation, as reflected in high R&D spending, development of cutting-edge technologies in several areas, and trailblazing development of digital economy. However, to become a global innovation champion, China will need to continue to improve its innovation capability in at least six other areas: enhancing government capabilities, balancing national and regional support for innovation, investing in basic research, leveraging open innovation, facilitating technology diffusion, and improving managerial practices, now discussed in detail.

Enhancing Government Capabilities

Public institutions that design, implement, and evaluate public innovation-support policies can reduce market failures and lower coordination failures. Yet the importance of such institutional capacity is often underestimated.

The capacity of innovation-supporting institutions can be assessed across four dimensions (Cirera and Maloney 2017, p. XXII): research that leads to scientific discovery.

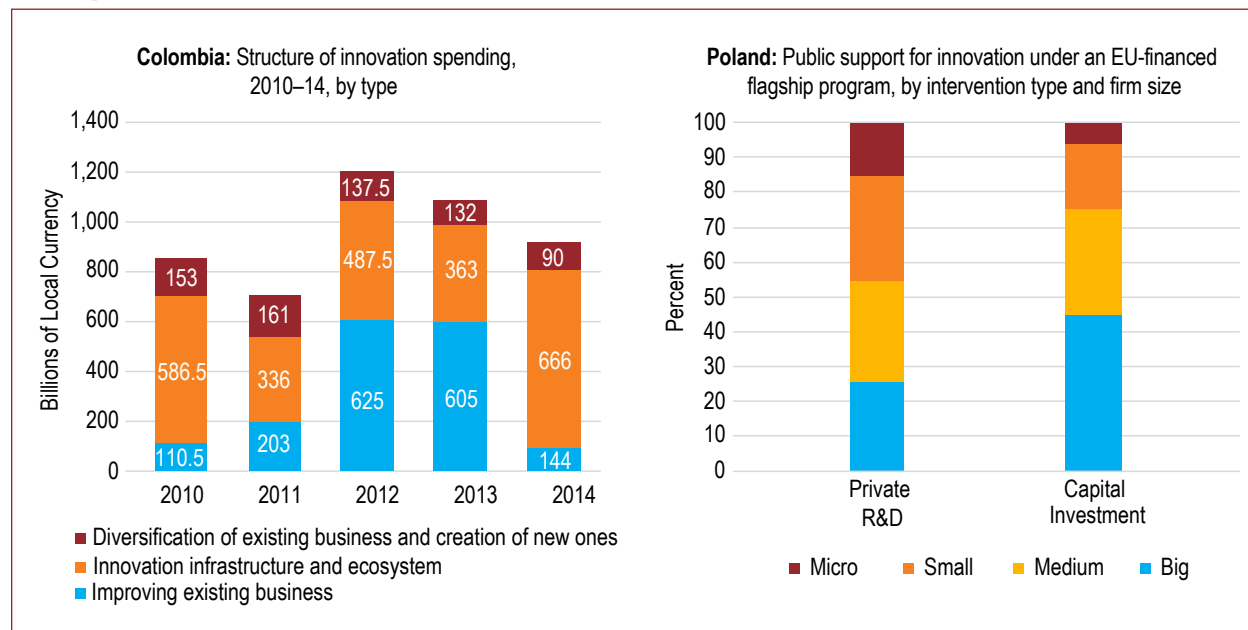
- Policy design, including the ability to identify market failures and key measures needed to address them.
- Implementation quality, including the availability of robust M&E systems that can prove the “value for money” of public investment and of well-aligned performance incentives.
- Policy coherence, especially the links between government strategies, policies, and instruments, and the quality of coordination among the key institutions.
- Policy consistency and predictability, ensuring that public support policies do not change with each new government.

In practice, many countries fail to build innovation-support systems with enough institutional capacity to meet the government’s objectives. Public support policies are often fragmented, duplicative, and

inefficient, leading to little alignment between the policy objectives, budget allocations, and final results. When the World Bank and Colombia, for instance, jointly reviewed the country’s innovation policies, they found that the government’s objective to leverage innovation to diversify the economy from natural resources was not reflected in increased budget allocations for diversification. In 2014, spending on diversification came to less than 10 percent of total innovation expenditures (figure 10, left panel). In a similar vein in Poland, there was little alignment between the government’s intention to support R&D spending in SMEs, where market failure is the largest, and the fact that more than 40 percent of spending under one of the flagship innovation support programs ended up financing capital investment in *large* enterprises, where market failure hardly existed (figure 10, right panel). Most other countries face similar challenges.

Steps to avoid fragmentation, duplication, and inefficiency would have a high payoff—given the plethora of policies and initiatives supporting innovation by different levels of government in China (more than 170 innovation policies at national level alone, as noted), and given that China will continue to get closer to the technology frontier. One approach would be to empower an agency with oversight and decision-making authority to serve as a national clearinghouse for innovation programs and projects above a certain amount of funding. This would be in line with good international practice, with most developed

Figure 10: A Lack of Alignment Between Program Objectives and Budgets Hampers Outcomes



Sources: Cirera and Maloney 2017. Cirera and Maloney 2017 and Kapil et al. 2012.

countries concentrating their innovation policies in a few institutions or coordinating the policies closely (Paic and Viros, 2019). In Korea, while many ministries are involved in innovation policy, the Ministry of Science, ICT, and Future Planning and the Ministry of Trade, Industry, and Energy are responsible for around two-thirds of total R&D spending.⁴⁶ In addition, the National Science and Technology Commission, headed by the prime minister, coordinates national innovation policies; it also helps analyze impacts of national R&D programs and instruments to adjust R&D budgets (OECD, 2014). Support for enterprise innovation is largely concentrated in the Korean Institute for Advanced Technology, established in 2009 after a merger of six public institutes.⁴⁷

Other developed countries have made similar attempts to streamline their innovation policies at the national level, while decentralizing them to local levels (OECD, 2015). Finland, Ireland, Singapore, and Israel concentrate decision-making and R&D funding in only a few agencies. True, these are small economies and in larger countries there is greater dispersion of policymaking and allocative

responsibilities, but the bulk of the research effort is still managed by few agencies. Even in the United States, just three institutions—the Department of Defense (DoD), National Institutes of Health (NIH), and Department of Energy (DoE)—are responsible for more than two-thirds of federal R&D spending. And the five top institutions are responsible for almost all spending. Similarly, support for basic research (discussed later), is largely garnered by only a few agencies.⁴⁸

One way to streamline policies in China would be to follow most developed countries and set up a new innovation agency, or upgrade an existing institution to focus on high-value-added support for enterprise R&D. While there is no single blueprint for how an innovation agency ought to look—much depends on the circumstances of each country—most innovation agencies benefit from the ability to concentrate top-notch know-how, human resources, and advanced financial instruments that respond to the increasingly sophisticated innovation needs of enterprises (Glennie and Bound 2016; Kapil and Aridi 2017). They also reduce red tape and information and coordination failures by becoming

one-stop shops for funding and for support to the enterprise sector. As research and innovative activities become more global, innovation agencies are also natural partners for supporting international cooperation. And such agencies can deal with the “indivisibility” of R&D spending, which demands substantial investment outlays for selected R&D projects to reach required scale. Given the already significant institutional complexity in China, upgrading an existing institution to become a one-stop-shop for enterprise innovation would likely be the most beneficial option.

Strategic, regulatory, and analytical aspects of innovation policy could remain vested among the existing institutions and coordinated within groups and committees headed by the premier or a vice premier, such as the Leading Group of Science and Education of the State Council.⁴⁹ The coordination mechanisms between all existing entities should also be strengthened, based on international good practice (OECD, 2014b). Many countries, such as Australia, Japan, and Korea, use roundtables or policy councils to coordinate innovation policy horizontally and vertically. Japan and Korea use high-level policy councils to take strategic decisions; in other countries, the policy council plays more of an advisory role.

China is well placed to complement its traditional approach of targeting strategic industries with horizontal reforms. Policies to promote new technologies (including R&D tax credits) should be open to all sectors, regardless of their “strategic” value. Because tax credits help mostly large and established companies that have enough taxable income and administrative capacity to apply for credits, support programs for start-ups and SMEs should include other instruments such as grants, vouchers, and collaborative networks.

This is the case in most developed countries, where flagship innovation agencies have considerable discretion over the focus of their support. In Sweden, 80 percent of spending by VINNOVA, the country’s innovation agency, is administered by the agency. The government decides only on the remaining 20 percent, but even there it uses “brushstrokes rather than detailed instructions”.

(Glennie and Bound 2016, p. 69). In Switzerland and Finland, innovation agencies decide on budget allocations for innovation support programs and projects based mainly on the recommendations of panels of experts from industry, academia, and civil society, rather than the government. Innovation agencies also spend significant budgets with no prior sectoral allocations. For instance, TEKES, Finland’s leading innovation agency, spends around 40 percent of its annual budget on “responsive” investments—projects that do not fit any specific government strategy. Israel’s Office of the Chief Scientist even goes a step further: regardless of sectoral provenance it bases its support for all projects solely on the capacity to generate new technologies with substantial growth and export potential.

Many larger countries also have specific arrangements for national–regional coordination. Spain, for instance, relies on collaboration agreements between state and regional governments, which align the parties along the key innovation priorities, provide targets for innovation policy, and coordinate budget allocations. Most developed countries also use other forms of coordination, most often through national strategies, a dedicated agency or ministry, and policy evaluations—or a combination of all three (figure 11).

Strengthening policy evaluations and reviews of innovation policy in China is another way to enhance coordination and improve the quality and impact of innovation policies. Policy evaluations in particular should be based on rigorous M&E frameworks. The lack of such frameworks is one of the reasons for the misalignment between public policy and its results.

Many countries, including China, have yet to develop these frameworks, which can provide ongoing feedback on the performance of the innovation support system and assess, to the extent possible, the return on public investment. Experience gained by the United States in implementing the Government Performance and Results Act of 1993 indicates that research is inherently difficult to evaluate because its purpose is to enlarge knowledge and understanding of a subject. Practical outcomes need not materialize for years, and some research may show that certain

Figure 11: Priority Forms of National Innovation Policy Coordination, 2012



Source: OECD Science Technology and Industry Outlook 2012.

Note: Based on own-country ratings, where 7 = high importance, 1 = low importance and 0 = nonexistent.

devices or processes being sought cannot actually be produced—which, while negative, remains a valuable result. Government agencies in developed countries therefore rely on expert review to evaluate research while it is in progress, with respect to quality, relevance, and whether the research is at the international technological frontier (when such criteria can be applied appropriately).

A RAND Corporation review of several OECD country research frameworks and tools concluded that research evaluations are generally conducted under four rationales: “(1) Advocacy: to enhance understanding of research and its processes among policymakers and the public; (2) Accountability: to show that money has been used efficiently and effectively, and hold researchers to account; (3) Analysis and Learning: to build an evidence base on research effectiveness and relevant support mechanisms to inform policy decisions; (4) Allocation: to determine where best to allocate funds in the future to get value for money”. (Guthrie et al., 2013).

Evaluation can be improved by delineating its purpose and by establishing transparent procedures and rationales to verify the results obtained, including longer-term impacts with the help of longitudinal studies. The timing of evaluation needs to be coordinated with performance reports.

There is a need also to incorporate explicitly the development of human resources as an objective of research and to continuously refine methodologies through the process of learning. And for the evaluation to improve decision-making, the findings need to be incorporated into the ways agencies plan their research activities, share information across agencies, and coordinate their activities to steadily enhance research productivity.

Evaluation based on rigorous methodologies has proven helpful in measuring the impact of innovation policies and their additionality (that is, the extent to which their impacts go beyond what would have occurred without them). The United Kingdom was the first to begin assessing research by universities through its Research Assessment Exercise, now the Research Excellence Framework, which evaluates research by all 165 higher education providers in the country along three criteria: quality, impact, and vitality of research environments, with the help of peer reviews. The STAR Metrics framework⁵⁰ in the United States has the tools and a repository for data on research projects that enable the NIH and the NSF, with assistance from the Office of Science and Technology Policy, to weigh the impact of research while minimizing the burden of data collection. A framework developed by the Canadian Academy of Health Sciences is another example of how

governments can track and measure the benefits from research (CAHS, 2011).

Other frameworks are in use, too—notably the public expenditure reviews for innovation, jointly implemented by the World Bank and client governments in middle and high-income countries (box 2.3). A recent study on Poland, which used a regression discontinuity methodology to assess the impacts of the country’s program to support innovation activities, found that it “largely funds projects that would not otherwise get funded by other agencies or by the business–science consortia themselves, increasing the probability of a project being completed by almost 60 percentage

points”. (Bruhn and McKenzie, 2016, p. 2). The support program also enhanced science–industry collaboration, boosted patent applications, and increased the number of research publications—and helped commercialize project-related inventions (ibid.).

China could productively adopt an M&E framework based on the experience of Canada, the United Kingdom, the United States, and several other developed countries. It could become part of a larger effort to monitor systematically the efficiency and effectiveness of innovation policy,⁵¹ supplemented by public expenditure reviews of innovation policy (see box 2).

Box 2: Public Expenditure Reviews of Innovation Policy

Public expenditure reviews (PERs) can help countries improve the quality of their innovation policymaking, improve resource allocation across programs, achieve budget savings, and enhance program impact. PERs evaluate four stages of innovation policy interventions:

- General evaluation of the quality and coherence of the policy mix based on the conditions of the country and its innovation system, including the portfolio mapping of STI programs and their assessment based on coherence with existing innovation policy objectives.
- Evaluation of the quality of design, implementation, and governance (functional analysis) of existing instruments based on good practices.
- Evaluation of the efficiency of existing instruments, meaning their ability to produce the expected outputs with reasonable levels of resources.
- Evaluation of the effectiveness of existing instruments and the system, by analyzing their ability to generate the desired impact.

Unlike traditional PERs, innovation PERs have the individual innovation policy instrument as the unit of analysis, which allows evaluators to identify what is spent with what objectives, and thus efficiency and effectiveness at a more detailed level. Their main objectives are to:

- Support the process of redesigning and shaping public innovation policies by using data and information on existing instruments.
- Improve the ability of governments to coordinate innovation policies by evaluating the design and implementation process and assessing the quality of the M&E system.
- Support the adoption of good practices in design, implementation, and coordination of innovation policy instruments by benchmarking instruments across countries (where appropriate).
- Formulate policy recommendations to strengthen the innovation policy mix by eliminating redundancies and leveraging complementarities across the portfolio of instruments.

Source: Cirera and Maloney 2017.

Balancing National and Regional Support for Innovations

As China moves up the technological ladder and productivity displaces capital investment as the primary driver of growth, a national innovation strategy can provide the ground rules and a large part of the financing for innovation. But given the uneven distribution of innovation across the country, every region will need to complement national initiatives by crafting its own policies to foster innovation—that is, to develop or deepen a regional innovation system (RIS).⁵²

With so many administratively delineated regions in China trying to create functioning RISs, there is an urgent need for a precise characterization of what an RIS is, the enabling conditions that facilitate its formation, and policies that can stimulate innovation by firms and their supporting institutions.

An RIS, as a subset of the NIS, can be described as a “production structure embedded in an institutional structure in which firms and other organizations are systematically engaged in interactive learning”, (Doloreux and Partob, 2005) or as “a place where innovation activities are concentrated and networked, creating a context-specific environment that fosters the production of knowledge with a systemic configuration”, (Prodi, Frattini, and Nicolli, 2016) or as “sticky place in slippery space” that nurtures, attracts, and retains firms that innovate and grow (Markusen, 1996).⁵³ Almost invariably—as in China—an RIS is anchored in major urban centers that may also host special economic or technology zones.⁵⁴ Cities with colocated—and possibly interlinked—clusters are advantaged. So are cities that house clusters at different stages of the life cycle, allowing new clusters to succeed mature or declining ones and take advantage of their learning and workforces.

The more advanced RISs in China began to germinate in special economic zones such as Shenzhen and in “open cities” such as Shanghai and Beijing. Large urban agglomerations have proven especially conducive to forming industrial clusters and ecosystems, sometimes a fertile source of commercially viable innovation because of

their close geographic proximity to universities and research institutions.⁵⁵ These agglomerations benefit from urbanization economies⁵⁶ and a variety of service providers that are important innovators contributing an increasing share of the value added by manufacturers.⁵⁷

Many and varied are the makings of an RIS. A start-up that grows into a major firm and that creates a cluster of suppliers and competitors can launch a regional system, as can government policy that locates research and manufacturing activities in a particular area. The defense industry in the vicinity of Chengdu is at the core of an RIS; Shenyang serves as the axis of another. An RIS begins acquiring traction once key firms that compete on the basis of innovation start scaling up, generate spillovers, and crowd in other activities. This is more likely in a large, diversified industrial centers and, as Shenzhen and other southern special economic zones show, a strategically located technology zone can become the hub of an RIS.

European and American RISs also identify research universities as building blocks because they are the principal sources of human capital and conduct much of the upstream research.⁵⁸ Most effective are universities and other research institutions integrated into a “triple helix” that ties together firms, universities, and businesses engaged in manufacturing and allied producer services (Etzkowitz, 2003). An interactive helical structure lends added impetus to regional innovation. Such a structure has emerged in Beijing, Shanghai, and Shenzhen, and policy incentives nudge firms in other regions to link with universities, though this remains a work in progress.

A second factor that affects the dynamism of an RIS is foreign direct investment (FDI), which in China has introduced new technologies through vertical spillovers, helped build ecosystems of local suppliers, accelerated accumulation of intangible capital that undergirds innovation, and enabled China to become a leading exporter of medium- and high-tech manufactures (Enright, 2017). Regional innovation has also benefited from policy initiatives that improve the business environment by pruning regulations, providing stronger IP protection, using

public procurement to launch new products and services, and setting standards that build product quality, reliability, marketability, and brand image.

As the pace of innovation activity quickens in China, an increasing share of overall spending will be subnational, with provincial and municipal authorities playing a larger role. In the recent past, there has been a marked tendency for provincial authorities to take their cues from the central government and to set their priorities accordingly. Regional research thus tends to be duplicative, wasting resources and human capital. This needs to change.

Regional innovation in China is more likely to make the best use of research financing and deliver growth if each regional entity takes the broad central government directives as the point of departure, and tailors its innovation strategy to its existing urban industrial base, research capabilities, and entrepreneurial potential.⁵⁹ Not every region can engage in cutting-edge research, however, and not every region needs to focus on the most advanced technologies. Specialization and collaboration with researchers in other regions and abroad can make research more productive and lead to innovations that local firms can commercialize. The trick is to recombine available resources in new ways. Smart specialization, implemented regionally in the EU, could be a source of inspiration for Chinese regions and help them identify regional endogenous strengths around which to build their support (World Bank, 2016).

Better coordinating private entrepreneurship and public research could yield more usable patents and profitable innovations. An organization comparable to the Georgia Research Alliance⁶⁰ would enhance the productivity of subnational research by coordinating the activities of public and private entities. And it could increase the contribution of universities to applied research and product development, directly assisting firms in commercializing their ideas (Chen and Guan, 2011).

What else can translate research findings into products and services? Local support services, sponsored and in part financed by provincial and municipal authorities, can provide firms with

searchable databases, national and international market intelligence, measuring and testing equipment, and a means for entering joint purchasing partnerships that reduce their costs. Standards for products and their certification can also help firms—especially smaller ones—meet quality requirements and thereby lower market entry barriers (OECD, 2008). Many of China’s budding “gazelles” lack the capacity to produce high-quality products and achieve large-scale distribution, particularly in markets abroad. This is where public–private partnerships (PPPs) and collaboration across regions would be valuable.

RISs in China now tend toward insularity, and nationally mandated efforts to localize technologies could make RISs even more inward looking. A more open innovation system would more likely lead to smart specialization of R&D. Chinese cities that have been more open to FDI, promoted joint ventures, and encouraged learning by exporting have proven more innovative. They have used MNC-linked GVCs to acquire and improve new technologies, scale up production, and enlarge their global footprint. The lesson for RISs in the making is clear. Specialize in the region’s strengths; use PPPs to enhance entrepreneurial activity; coordinate research activities; and keep the system open so that local researchers benefit from research elsewhere and collaborate with researchers worldwide.

Investing in Basic Research

Governments and the research community know that large private firms—with the time horizon and the resources to conduct basic research—have been cutting back on their in-house activities and looking to publicly supported universities, research institutes, and start-ups to close the gap (Arora, Belenzon and Pataconi, 2015). Indeed, much of the EU’s research to expand the frontier of discovery now takes place at universities and in public laboratories.⁶¹ But research can generate large social returns.⁶² Basic and applied research are intertwined, so pushing hard on applied research to the neglect of basic research—as many firms and universities are now prone to do in pursuit of near-term commercial payoffs—can lead to diminishing returns.⁶³

Some argue that the most productive years of Bell Labs were when R&D was conducted under the same roof by a critical mass of exceptional researchers with considerable leakage between the two sides of R&D and with researchers “having the flexibility to move between research domains [and] between R&D when it was productive to do so”. (Narayanamurti and Odumosu 2016, pp. 46-47; Gertner, 2012). Researchers also enjoyed the freedom to pursue projects of their own choosing because the monopoly enjoyed by the parent company AT&T meant that there was little pressure to restrict research to projects that promised a commercial return. The DARPA model also promotes parallel advances in pure science and in technology development by identifying a high-risk/high-payoff objective, as in information technology, sensor systems, cyber security, robotics, new materials, and directed energy systems.⁶⁴

Basic research is essential in, for example, furthering the development of quantum computing and communications in enhancing cybersecurity,⁶⁵ in fighting infectious diseases increasingly resistant to the most potent antibiotics, in finding new catalytic materials (possibly using protein-derived enzymes) for improving industrial catalytic processes,⁶⁶ and in discovering new and commercially viable battery technologies (such as replacing lithium with sulfur).⁶⁷ Spillovers from the Diamond Light Source—a third-generation synchrotron in the United Kingdom—increased the productivity of scientists (measured by publications) within a 25 km radius of the facility by 11 percent over 10 years (Helmets, Christian and Henry Overman, 2017). Research published in *Science* provides further empirical support for the links between patenting, innovation, and earlier scientific discoveries (Ahmadpoor and Jones, 2017).

China has 1,000 research institutes and as many as 1,000 universities that can, in principle, conduct basic research (Yang, 2016). Yet, China’s contributions to original, frontier-pushing innovation to build the base of scientific discovery received only about 5.6 percent of total spending on R&D in 2018.⁶⁸ Research universities, which could do more of the groundbreaking research, accounted for just

7 percent of the R&D spending (OECD, 2017). Most of the growth in R&D spending is from “experiment and development” spending by large firms that typically do very little basic research (figure 2.27, left panel). At the same time, the United States allocates 17.6 percent of its R&D to basic research, Japan 12.6 percent, and France 24.1 percent. OECD countries spent about 17 percent of total R&D outlays on basic research, 21 percent on applied research, and 62 percent on experimental development. China’s spending on basic research was much lower (figure 12).

That basic research is beginning to receive more attention and funding in China is apparent with several research facilities coming online. The synchrotron light source in Shanghai is enabling researchers to better understand the structure of proteins and cell metabolism (*Nature*, 2017a, 2017b). The Spallation Neutron Source and China’s Advanced Research Reactor can further basic research in important areas. China is rightly moving at a measured pace in scaling up basic research as it builds human research capital of the highest caliber. Investment in expensive equipment that sits idle is best avoided. And while the social returns to R&D remain high, the “bang for the buck” from research is on a downward slope, with research productivity declining 4–6 percent a year (Bloom et al. 2017).

Consider the EU’s Horizon 2020, a seven-year €75 billion program managed by the European Commission to enhance innovation in the EU and develop research capital. The research activities have the material support of the private sector and engage researchers from 130 countries, building an extra-European network that taps expertise from across the world. Horizon 2020 has supported 17 Nobel prize winners and the publication of numerous scientific papers, patent applications, and key research findings, such as the discovery of new exoplanets, the Higgs boson, and gravitational waves. Because it restrains red tape and transaction costs, it caters to SMEs, which consume a quarter of the funding. A recent internal evaluation established that 83 percent of the projects financed would not have gotten off the ground without funding from Horizon 2020. It is also estimated that each €1 from

Horizon 2020 generated €6–8.5 of GDP and that the benefits accrued to the EU could amount to €600 billion by 2030 (European Commission, 2017b).

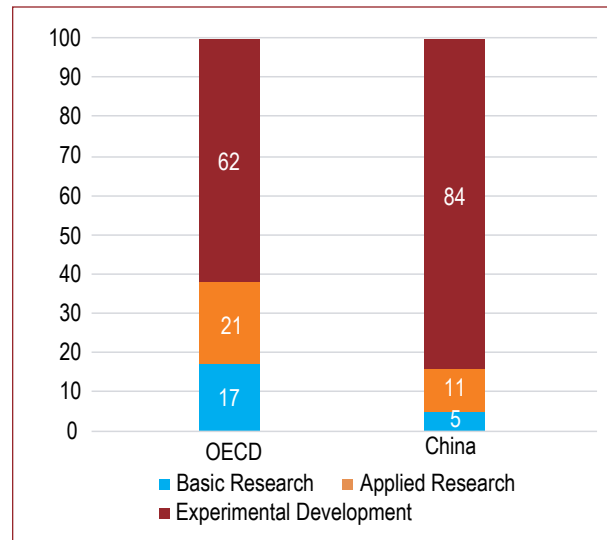
China could also review this experience and that of other large countries such as the United States, which finances basic research mainly through the NIH and NSF, responsible for more than 60 percent of annual spending on basic research.⁶⁹ While the NIH has a focus on biomedical research, the NSF supports all types of research involving science and engineering. Both institutions independently determine which areas of science are the most promising and would provide the largest economic payoff. The NSF identifies research projects through a bottom-up approach, based on a constant monitoring of the changing research trends in the United States and in the world. Project selection draws on merit review, considered the global “gold standard” for scientific review.⁷⁰

Leveraging Open Innovation

Many innovative ideas are not the result of a given firm’s own efforts but instead come from outside: from customers, partner firms, suppliers, universities, and others. Almost any complex product today incorporates inputs from researchers and firms in different economies—the iPhone is one frequently cited example, with firms from China, France, Japan, Korea, Taiwan China, and the United States producing key components assembled in China by Foxconn (Gould and Villas-Boas, 2016).⁷¹ ICT advances have made it far easier to network, collaborate, and crowdsource, with the emergence of pockets of specialized scientific and engineering expertise in developing economies that can now be drawn into collaborative ventures or tapped through crowdsourcing channels.

By dispersing R&D activities across countries, MNCs can shave costs, achieve around-the-clock operations, and harness expertise that may be scarce in their home countries. For companies—or countries—that want to stay at the frontier of scientific research, collaborative research and interaction among researchers is the only sure way to stay abreast of the latest thinking and the

Figure 12. China’s R&D Spending for Basic Research vs. the OECD Average



Source: Colin 2017 and OECD 2017.

“hottest” technological developments. The reasons? Even in today’s world, the most advanced scientific knowledge diffuses slowly, and a great deal of it can remain tacit, diffusing by word of mouth (Adams, Clemmons, and Stephan 2006).

With the advantages of openness more widely appreciated, R&D in advanced countries has tended toward greater cross-border collaboration (Hale, 2012). Close to a fifth of spending on research by national governments is on international projects and in some instances it can be more than one-half (Wagner and Jonkers, 2017). International collaboration enhances the citation impact of research, because researchers of the highest caliber and productivity are thinly distributed and among the ones more likely to collaborate with the best researchers in other countries (Adams, 2013). Two-thirds of the scientific output of Switzerland—consistently ranked among the world’s most innovative and competitive economies by the World Economic Forum—involves collaboration with outsiders. Open economies produce the most high-impact research, while in less open ones, including several large emerging economies, almost three-quarters of research tends to be domestic, generating much less impact (Fleming, 2017).

China has been one of the foremost beneficiaries of the open and global innovation system, but Chinese firms are now viewed as competitors by their counterparts in high-income countries. Chinese researchers trained in the United States, Europe, and Japan have been conduits for knowledge transfers, and collaboration with foreign scientists has helped Chinese scientists climb the citation indexes and narrow technology gaps. China has been strikingly advantaged by co-ethnic cooperation between the almost 100,000 holders of doctoral degrees in STEM disciplines in the United States of Chinese origin and scientists based in China (Gupta, 2016).

Collaboration is by no means a one-way street. With Chinese researchers gaining experience, the quality of equipment in Chinese labs is improving markedly. And with research funding becoming more plentiful, U.S. researchers, especially younger ones struggling to mobilize grant funding, are collaborating with Chinese scientists to further their own research (Gupta, 2016). By opening satellite campuses in China, western universities such as NYU, Monash, Liverpool, and Duke⁷² have facilitated even more collaboration. And the connectedness of China with its international diaspora is tight: Chinese scientists are linked to others in 94 countries (Nature, 2015).

In the future, an open global innovation system will remain critical to sustaining China's economic growth and helping to meet the country's two "centenary goals". Given the diminishing returns of additional public investment and gradual decline in the size of the labor force, productivity growth will need to become the main engine of China's growth. Faster productivity growth will in turn need to be supported by an open innovation system that promotes the absorption, diffusion and development of new technologies.

But in many ways China seems to have come to a crossroads in its development based on absorbing foreign technology and participating in the open global innovation system. It could be argued that under the current, open system China has been able to gain from the open global innovation system, while keeping its market largely protected, progressing with indigenization of technologies

and taking steps toward becoming technologically autonomous. These two goals may become increasingly incompatible, especially as China is no longer perceived as a "developing country" and as many of its industries, companies and regions (especially at the coast) are seen (and acknowledged by the Chinese authorities themselves) to be closing in on the global technology frontier. By dismantling the barriers that shelter domestic firms from foreign multinationals (a protection that is rapidly becoming redundant if not counterproductive), China would in one stroke stimulate the capacity for innovation of Chinese enterprises, increase the level of productivity by enhancing market competition and eliminate a major source of friction with its trading partners. Developments during the past three years indicate that China's partial globalization has outlived its utility. An industrially mature China can confidently embrace globalization in its entirety by matching the openness of the advanced economies with which it is now drawing abreast.

What can China do to keep the global innovation system open and continue to benefit from the global technological progress? While some developments are driven by exogenous factors that China cannot control, there is much that China could do on its own.

First, it would be in China's interest to continue to strengthen international norms that govern international economic relationships and promote dialogue. China could help these efforts by fully aligning itself with WTO rules, including those on industrial subsidies, treatment of SOEs, and regulations that give rise to non-tariff barriers to trade and strengthening enforcement mechanisms (Grossman, McCalman, and Staiger, 2019). Policies that may be in conflict with WTO SCM Agreement or otherwise against the principle of competitive neutrality should be reviewed, modified or phased out as appropriate. China could also spearhead efforts to further develop international norms governing cyberactivity.

Second, China could "lead the world by example" by fully opening its markets, ensuring a level-playing field for all companies, including for private and foreign-owned companies, strengthening

effective IP protection, and making public support policies transparent. All these measures would not only help reinvigorate the growth of the domestic economy, including that of the private sector, but at the same time also lessen other nations' fears of an "unequal playing field" and thus help keep the global innovation system open.

Third, China could further promote global cooperation on science and innovation. This could include mechanisms to increase investment in international collaboration in basic research on global public goods (such as green technologies, medicines and others), funded by, for instance, a newly established global innovation fund. Another fund could help finance global scientist exchange programs modeled on, for instance, the European Union's successful Erasmus student exchange program.

Finally, China might reconsider its indigenizing policies to capture as much of the manufacturing value chain as possible. Some technological autonomy is desirable for a major economic power, as with technology development catering to major infrastructure projects heavily oriented to a large domestic market, such as high-speed rail (Liu and Cheng, 2011). But much like import substitution carried to an extreme, it can rapidly become counterproductive, a waste of resources spent in rediscovering known technologies, and break down trust and collaboration with other countries—aside from potentially triggering trade disputes.⁷³ While in a static view the advantages for China of mastering all technologies and promoting global technological champions may promise larger benefits than those proffered by an open global innovation network, in a dynamic view where other countries react to such an indigenization strategy, the apparent benefits may be outweighed by the losses resulting from the reactions of other players, especially the leaders of the global innovation network. The win-win solution could be to engage other countries in China's efforts to develop new technologies, including core technologies, and ensure that other countries do not see China as a country that aims to monopolize the commanding heights of global innovation and exclude other nations in the process.

Facilitating Technology Diffusion

Adapting to constantly changing technology and preparing for growing disruption requires a combination of policies aimed at technology transfer, science–industry collaboration, and R&D- and non-R&D-based innovation. It also requires the skills and managerial competencies to maximize firms' capacity to innovate and absorb technology. The majority of potential productivity gains in developed countries (55 percent) appear to be derived from adopting best practices and technologies rather than by developing new ones (Dobbs, Manyika, and Woetzel, 2015). Mechanisms to support the diffusion of new and existing technologies range from broad management extension services to more sophisticated R&D institutions, and more recently to technology information and collaboration platforms (Youtie and Shapira, 2017).

The broader management and dedicated field extension services, such as the Manufacturing Extension Partnership in the United States (see below), tend to follow a model similar to traditional agricultural extension services, and support building the capacity of SMEs to absorb existing technologies. One step above, at least on technological focus, are technology extension services that concentrate more narrowly on technology adoption, for example of specific digital technologies, and not on broad absorptive capacity. For more specialized technologies, OECD countries have technology and R&D centers. Some technology centers, such as those in Catalonia, Spain, arose from PPPs to solve technological problems and develop solutions for specific sectors or clusters. The centers tend to be very specialized in specific technologies and are managed as a network, as with the Fraunhofer Institutes in Germany, a network of 60 private nonprofit research institutes that do contract research for the government and for business organizations (Shapira, Kwon and Youtie, 2017). But the capabilities of the Fraunhofer Institutes are inseparable from the strength of Germany's engineering sector. Without strong capabilities in the private sector, implementing these models in other contexts may be difficult.

Empirical evidence on the effectiveness of the various mechanisms is scarce, however. There are just too few evaluations, and those that exist have focused on a few policy instruments, such as some business advisory or R&D schemes, rather than broader evaluations. A few successful experiences have been documented in East Asia—Japan, Korea, Singapore, Taiwan China, and China to certain extent—where a significant share of the private sector has upgraded its technologies.

Effective technology diffusion requires going beyond process innovation to include other types of innovation, as in business models or in marketing, encouraged by grants. Although often more related to product innovation by helping to finance activities ranging from development, prototyping, viability, or commercialization, the support has also financed the introduction of new production processes. Many countries use matching grants and technical assistance to facilitate digitization of SMEs, sometimes by partnering SMEs with large ICT companies. Similarly, vouchers can incentivize the collaboration of SMEs and knowledge providers in starting the implementation of Industry 4.0 processes. Grants, usually smaller, have financed the collaboration of SMEs with local consultants or universities in supporting technological needs within the SME. Again, however, the evidence is limited on the effectiveness of these approaches, particularly the adoption of complex technologies. Studies in OECD countries show positive effects of input additionality—additional innovation activities—and positive but very scarce impacts in relation to outputs and outcomes—introductions of new processes and increases in productivity (García-Quevedo, 2004; Zúñiga-Vicente et al., 2014; Becker, 2015).

Today, France, Germany, Japan, and the United States are leading the efforts to deploy existing and new policy instruments to facilitate the adoption and diffusion of advanced technologies, though Brazil and China are also making deep inroads.⁷⁴ The first steps in these efforts are to set up a central secretariat or platform that orchestrates all efforts around Industry 4.0, to conduct foresight studies, and to create national plans involving multi-stakeholder working groups. Germany and the United States

provide leading examples of creating integrated approaches to deploying policy instruments (BMBF 2017; GTAI 2017).

The United States, for example, launched the Advanced Manufacturing Partnership 2.0 (AMP 2.0) in 2011. This is a “national effort bringing together industry, universities, and the federal government” (White House 2011). Comprised of 19 industry, academia, and labor representatives, the AMP steering committee published a report in 2014 titled “Accelerating U.S. Advanced Manufacturing”, which advances policy recommendations on skills building, research, and technology adoption. Overseeing the implementation of these recommendations is the Advanced Manufacturing National Program Office as part of the National Institute for Science and Technology, with its Manufacturing.gov platform. It coordinates multi-stakeholder initiatives, such as the Advanced Manufacturing Technology Consortia (AMTech), a grant program for research consortia; MForesight, a mechanism for soliciting forward-looking private sector input on R&D priorities; the Manufacturing Extension Partnership (see below); and Manufacturing USA, a network of 15 Manufacturing Innovation Institutes, of which nine have been established (and a further six were scheduled to open in 2017).⁷⁵ These institutes are PPPs and received US\$600 million in federal and US\$1.2 billion in nonfederal funding in 2016. They provide access to state-of-the-art facilities and to workforce training and skills development so as to shepherd technologies from the research to the adoption stage (Manufacturing.gov 2017).

Governments also support R&D via tax credits, innovation vouchers, public procurement programs, and access to testing facilities. Japan and the United States provide research tax credits (OECD 2016), while Europe and the United States have provided incentives for firms to purchase R&D services and expertise through innovation vouchers (Shapira and Youtie 2017). The United States has a public procurement program run by the Small Business Innovation Research program, spending about US\$2 billion per year on as many as 4,000 contracts with SMEs to spur technological innovation and commercialization (Rigby et al. 2013). Testing

facilities require more adaptation, as they are technology-specific and need to provide the right tools and equipment. In Germany, for example, there are now more than 500 “test beds” providing access to digital and physical technology relevant to Industry 4.0 as well as expert researchers (Industrie 4.0 2017). U.S. companies can access testing facilities through several of the Manufacturing Innovation Institutes, each focusing on a specific technological aspect of advanced manufacturing (President’s Council of Advisors on Science and Technology 2014).

A growing literature documents high-quality managerial practices as a key input and complementary factor for R&D outlays and firm-level innovation (Bresnahan, Brynjolfsson, and Hitt, 2002, Bloon, Sadun and Van Reenen, 2012, Bloom et al., 2017). Managerial quality can generally be strengthened by a range of measures including enhancing market competition, encouraging participation in GVCs and cooperation with MNCs, providing additional education to managers, increasing exposure to international markets, and improving bankruptcy procedures to facilitate exit of the weakest performers. Diffused ownership of firms also helps, as it provides stronger incentives to managers than state or family ownership.

Governments also directly support improvements through management extension programs. These involve advisory services that benchmark companies according to an agreed benchmark of the quality of management practices (such as the World Management Survey or Management and Organizational Practices Survey, with the latter increasingly incorporated as a module in national firm surveys), provide a business plan on how to improve management skills over a given period, and support firm management in implementing the business plan. Such extension activities, inspired by the successful diffusion of agricultural technology, have been widely adopted. In Germany, Mittelstand-Digital helps SMEs understand the advantages of digital applications and take concrete steps toward Industry 4.0. It does so primarily through more than twenty “SME 4.0 competence centers” that demonstrate how digitization, innovative networking, and Industry 4.0 can be used in business practice. In Japan, 162

Kohsetsushi Centers provide free advisory services to SMEs as well as access to laboratories on a cost-sharing basis (Ezell and Atkinson 2011).

The United States supports technology diffusion through the Manufacturing Extension Partnership, a network of local centers in all U.S. states at 400 locations and with a staff of 1,600 that is funded from federal, state, and industry sources (Ezell and Atkinson 2011). In 2017, the federal funding portion of the budget was increased from one-third to one-half, a sign that the government is committed to expanding the program (Youtie and Shapira, 2017). The locations serve SMEs with services for process improvement, product development, marketing, training, and sustainability; and they connect manufacturing SMEs to other private and public assistance sources.

The Korean government’s Centers for Creative Economy and Innovation in 17 regions serve as one-stop shops for entrepreneurs interested in starting a business. They provide mentoring and incubating services for start-ups. Some of the centers are backed by strong local businesses (for example, Hyundai Motor with the center in Gwangju), while others include big data (Gangwon), bio-beauty (Chungbuk), and carbon (Jeonbuk). Box 3 looks at support services for businesses in Singapore.

Technology adoption is also supported by standards, which improve compatibility of assets and reduce the uncertainty of investments. Germany and Japan have prioritized the development of standards for Industry 4.0. In Japan, the Open Robot/Resource interface for the Network (ORiN) is being developed to make it easier to adopt smart connected factory technology (ORiN Forum 2016).⁷⁶ Three major German industry associations involved with the Industrie 4.0 Platform are advancing the development of the “Referenzarchitektur Industrie 4.0” (RAMI 4.0) or reference architecture, which is a first step toward standardization (ZVEI 2015; BMBF 2017).

Complementary efforts that ensure the supply of technical skills are necessary to maximize firms’ capacity to innovate and absorb technology. Germany and the United States have conducted reviews to determine the future workforce needs that

Box 3: Business Support Services In Singapore

Singapore provides a suite of instruments to SMEs that want to upgrade their capabilities, including managerial practices. SMEs start the engagement at the SME Centre, which is generally run by the trade association (chamber of commerce), where the SPRING agency covers the costs of the business development services that they undertake. As a first step, a business advisor visits the firm and provides a diagnostic suggesting the upgrading area and matching the SME to a local private sector consultant. As firms grow more sophisticated, they may be matched with an account manager in SPRING who acts as their “general practitioner”.

Singapore provides a broad menu of instruments to support upgrading through SPRING and A*STAR, depending on the sophistication of the SME’s capabilities. The former provides support to management upgrading to those firms primarily at the bottom of the escalator, whereas the latter combines instruments for upgrading technology in firms with more sophisticated capabilities.

SPRING offers the following to support and finance upgrading:

- **Online support and toolkit.** Enterprise One is a single-window portal that helps firms navigate the government’s programs. SPRING also has an online toolkit that includes self-help guides on customer service, financial management, human resource capability, marketing, and productivity
- **Innovation and capability voucher.** The entryway to government programs is a S\$5,000 voucher to upgrade and strengthen core business operations through consultancy projects in innovation, productivity, human resources, and financial management.
- **Loans.** These include the Micro Loan Program, Local Enterprise Fund Scheme, and Loan Insurance Scheme. The government pays 50 percent of the cost of insurance through a third party for trade credit or working capital. The Local Enterprise Finance Scheme helps SMEs secure financing for productive assets, working with a partner financial firm to get SMEs loans of up to S\$15 million for up to 10 years.
- **Capability and development grant.** This program covers from 0 to 70 percent of costs—up to S\$100,000—for technical upgrading. Eligible activities include consultancy, manpower, training, certification, upgrading productivity and developing business capabilities for process improvement, product development, and market access. There are 10 areas: brand development, business innovation and design, business strategy development, quality and standards enhancement, financial management, human capital development, intellectual property, franchising and productivity improvement, services excellence, and technology. Firms may apply to SPRING, and may be recruited by SPRING directly or through the chambers of commerce, which are on the lookout for promising firms.
- **Productivity and innovation credit.** Firms may either deduct 40 percent of investment or receive a cash payout of 60 percent up to S\$100,000 for each year in all six qualifying activities of investment, including acquisition of information technology and automation equipment, training of employees, registration of patents, trade mark designs and plant varieties, acquisition and in-licensing of intellectual property rights, project design, and R&D.

Source: Cirera and Maloney (2017, p. 175–76).

are now informing policymakers' efforts at shaping education and training systems.⁷⁷ The German Federal Institute for Vocational Education is funding the digitization of training centers and is running a two-year program with the Federal Ministry for Education and Research on “vocational training 4.0” to establish an impact screening of occupations and sectors, and a high skill labor forecasting system. Countries like Estonia and Finland are integrating digital skills into basic school education.

The Skills for America initiative has partnered with the Aspen Institute and the Manufacturing Institute—a nonprofit body affiliated with the National Association of Manufacturers—to help half a million community college students pursue training and credentials, making it easier for them to find work with manufacturing companies (White House 2011).⁷⁸ Additional specialized training is provided by the Manufacturing Innovation Institutes.

At the subnational level, ecosystem-based approaches are growing in prominence. For example, New York City responded to more than 90,000 in employment losses during the 2008–09 financial crisis by introducing programs to harness the laid-off talent to help build the second-largest tech start-up ecosystem in the country (after Silicon Valley), with almost US\$6 billion venture capital investment in start-ups and over 14,500 listed start-ups in 2015. The city government introduced mentorship programs, accelerators, incubators, coworking spaces, events, skills training programs, and other supporting services (Mulas and Arangué, 2016). This boom in the urban tech ecosystem evolved around the traditional local industries of the city (for example, finance, advertising, media, fashion, and health care), which not only enabled New York to retain specialized talent at a moment of crisis, but also increased the competitiveness and innovation of its traditional base.

北京

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SUMMARY OF POLICY RECOMMENDATIONS

China has achieved a remarkable success in promoting technology absorption and—for a few industries—spurring frontier innovation. This has helped support China’s rapid economic growth and transformation over the last three decades. To continue to develop at a fast pace and become a leading global power in innovation, in line with its ambitious plans as outlined in the Made in China 2025 10-year plan, China needs to address the existing shortfalls in its NIS and improve the translation of innovation inputs and outputs to productivity growth (table 2.4).

Each of the table’s specific recommendations can be implemented by learning from examples of international efforts. For instance, putting greater emphasis on diffusion of technology could be informed by the experiences of the Manufacturing Extension Partnership in the United States or Japan’s Kohsetsushi Centers. Public support programs to promote improvement in management skills could learn from the experience of Singapore’s SPRING agency. Efforts to streamline innovation policies

could be based on the public expenditure reviews in Colombia. Centralizing support for enterprise innovation could learn from DARPA in the United States and Israel’s Office of the Chief Scientist. And stronger involvement of the private sector in the design of innovation policies could be modeled on the EU’s smart specialization. Each of these recommendations would, however, need to be adjusted to China’s economic, institutional, and cultural context. One size will not fit all.

Table 3. China’s NIS Shortcomings and Policy Recommendations

NIS Shortcoming	General Recommendations	Specific Recommendations
Slowing productivity growth and widening disparities between productivity performance of top firms and the rest of the distribution	Put greater emphasis on facilitating diffusion of technology	<ul style="list-style-type: none"> • Develop a nationwide system for helping SME manufacturers upgrade their technology and capabilities • Design targeted support programs for SME collaboration with research institutes and universities, including effective industry liaison programs • Review the effectiveness of existing policies and institutions, strengthening those that work and eliminating those that do not • Promote market competition • Use public procurement to create markets for innovative products, especially for SMEs
Weak managerial capacity, particularly compared with top firms in advanced economies	Highlight continuous management upgrading as a core innovation competency	<ul style="list-style-type: none"> • Expand management-practice support programs based on international good practice • Introduce a support program to include awareness and best practice campaigns among firms, detailed benchmarking information for firms, and technology use, particularly in lagging regions
Limited collaboration across firms, and between firms and other NIS actors; challenges in acquiring advanced technology	Nurture a more open and globally integrated innovation system	<ul style="list-style-type: none"> • Expand support for interfirm, business–science, and international cooperation in research and patents • Further enhance the mobility of researchers, including travel and exchange programs
Greater need to develop own knowledge and increase quality of research outputs	Expand public R&D toward basic and “blue sky” research, and move from quantity to quality of research and patenting	<ul style="list-style-type: none"> • Increase the share of public R&D support devoted to basic research, in step with the improvement in the quality of human capital and the governance framework, including through greater support for universities and national basic research programs, such as the National Natural Science Foundation of China • Reduce the emphasis on targeting specific fields and technologies in favor of a more decentralized and bottom-up approach • Strengthen evaluation of research, making greater use of objective peer reviewing • Reward high-quality, rather than high-output, research • Redirect public support to high-quality domestic and international patents

Market and institutional failures in creating the right incentives for innovation and entrepreneurship, especially for SMEs	Strengthen IPRs, including stronger enforcement	<ul style="list-style-type: none"> • Expand the capacity and resources of the relevant administrative agencies and the court system, including specialized IP courts • Strengthen enforcement of court orders and formal judgments, including the levying of fines sufficient to change behavior • Encourage moving court cases to third-party jurisdictions in certain circumstances to avoid conflict of interest and further central initiatives to monitor and limit unfair court rulings • Promote nongovernment arbitration and mediation for IP cases
Prevalence of linear, top-down approaches to supporting innovation	Promote a more bottom-up, market-based innovation policy to deal with increasing unpredictability of technological development	<ul style="list-style-type: none"> • Complement the current approach to promoting innovation with a more market-based and private sector-driven innovation policy (for example, one based on the EU smart specialization concept), especially at regional levels • Make selected public support programs open to all industries and enterprises • Enhance support of ecosystems and expand the network of incubators organized around existing science and technology parks, with links to existing businesses and professional networks
Fragmentation of innovation policymaking and implementation	Consolidate and streamline innovation policies	<ul style="list-style-type: none"> • Streamline innovation policies and programs by carrying out a public expenditure review of STI, and restructure or eliminate programs that do not perform well • Consider upgrading an existing institution to centralize financing for enterprise innovation • Increase coordination of innovation policy by adapting global good practice to the Chinese institutional context
Limited penetration of rigorous M&E in design and implementation of innovation policy	Expand the use of M&E	<ul style="list-style-type: none"> • Increase the reliance of policymaking on rigorous, quantitative evaluations of policies, including evaluations of the innovation policy instrument mix, its functional design, efficiency, and effectiveness
Limited alignment of innovation policy instruments with firms' needs	Promote closer engagement of the private sector in designing innovation policies and support instruments	<p>Expand dialogue with the private sector, including by using government-business policy platforms and firm opinion surveys</p> <p>Experiment with new public support instruments, with an embedded expiry date to ensure periodic evaluation</p> <p>Expand involvement of private sector professionals in the selection process for public innovation support</p>



ENDNOTES

1. It took 30 years for electricity and 25 years for telephones to reach 10 percent adoption in the United States, but less than five years for tablet devices to achieve the same rate of adoption. It took an additional 39 years for telephones to reach 40 percent penetration and another 15 before they became ubiquitous. Smartphones, on the other hand, have accomplished a 40 percent penetration rate in just 10 years. According to some futurologists, we are at the threshold of a new technological epoch characterized by the endless acceleration of technical progress. See, for instance, Kelly (2016), Kurzweil (2005) and Diamandis and Kotler (2012 and 2015).
2. Bitcoin was created by an individual inventor or a group of inventors calling themselves Satoshi Nakamoto. Blockchain, as a technology, is essentially a repeatedly updated electronic ledger recording transactions of any kind.
3. https://www.uspto.gov/sites/default/files/aia_implementation/aia-effective-dates.pdf
4. See, for instance, World Bank (2016) for an example of such interaction through Smart Labs in Poland.
5. France, for instance, has revised its Government Procurement Law to strengthen support for innovation in medical instruments and help reduce costs. See, for instance, Georghiou et al. (2014).
6. The actual outcomes can be highly nonlinear. Kancs and Silverstovs (2015) show that initially the impact of R&D on firm productivity can be low—an elasticity of 0.15. However, as the critical mass of expertise and experience accumulates, productivity rises and the elasticity of response can go up to 0.33.
7. See Freeman, Marschke and Wang (2009) and Hall, Mairesse, and Mohnen (2009).
8. However, large outputs of patents do not necessarily follow from increased R&D spending. Hu and Jefferson (2009) found that the correlation between R&D spending in China in 1995–2001 and patenting was on the whole fairly weak. Hu and Jefferson also cite studies using U.S. and Japanese data that point to a weak relationship between patenting and innovation. Eberhardt et al. (2016) arrive at similar findings.
9. Bloom et al. (2017) point to declining returns from and productivity of R&D activity.
10. Boeing, Mueller, and Sandner (2016) argue that the increase in China’s R&D has yet to deliver TFP growth. See also Cirera and Maloney 2017.
11. Andrews et al. (2015) observe that a major reason why productivity is stagnating in Western countries is because the majority of firms in an industry are slow to adopt new technologies that firms at the frontier are already using, and lagging firms are also slow to exit.
12. The World Management Survey sample in China is not very large and comprises large manufacturing firms. Further research in this important area is needed.
13. There were at least 2,500 officially registered tech incubators in China (McKinsey, 2017).
14. National Medium and Long-Term Program for Science and Technology Development.

15. From: <https://www.nsf.gov/statistics/2018/nsb20181/report/sections/research-and-development-u-s-trends-and-international-comparisons/cross-national-comparisons-of-r-d-performance>. However, PPP measures can inflate R&D spending of China. Nonetheless, nominal measures would show similar trends.
16. These policies have been identified by searching for terms “science”, “technology”, and “innovation”, using the search method of “theme” and “exact match” in the law and policy database of Peking University.
17. According to Molnar (2017), the central government is responsible for about half of total public R&D spending, while SOEs are likely responsible for the rest.
18. <http://www.chinadaily.com.cn/a/201802/13/WS5a827ffea3106e7dcc13c829.html>
19. Based on the State Council’s ‘Opinions on enhancing basic scientific research’ issued in January 2018. See also http://english.gov.cn/policies/latest_releases/2018/01/31/content_281476032021752.htm
20. The data on the number of policy instruments are subject to two major caveats: first, they count the number of support instruments rather than their budgets (which were not available), making it hard to judge their relative importance; the data may also count policies, which despite a similar official title may in practice have a different focus.
21. 264 national engineering research centers provide technical assistance to SMEs in specific technology areas (Li, 2012).
22. Gazelle firms are midsized, fast-growing firms that frequently produce tradables, engage in exporting, and base their competitiveness on product and process innovation.
23. Preferential treatment of SOEs is likely to result from high risk aversion among the public support institutions, which prefer not to run the risk of dealing with the private sector; privileged access of SOEs to information on the funding instruments; predominance of SOEs in the priority sectors; and the ability of SOEs to influence government policy directly. These findings stand in contrast with the aim of government policy to shift to a more market-oriented approach to support innovation.
24. China had 4.7 million new graduates with degrees in STEM disciplines out of a total of 7.0 million graduates in 2016 (Stapleton, 2017).
25. There were only 18 students enrolled in PhD programs in 1978. Enrollment has increased annually by 23 percent since. The quality of the degrees awarded by many Chinese universities remains an issue as the number of qualified academics to supervise doctoral candidates has risen far more slowly such that, in 2010, the ratio of supervisors to students was 1:6, much lower than in Western countries. Further, it takes an average of three years to receive a doctoral degree in China against an average of five to seven years in Europe and the United States (Majumdar, 2014).
26. On defining and measuring the talent pool, see Simon and Cao (2006). Close to 3.5 million Chinese students have gone abroad to study and the government estimates that about one half have returned, including 110,000 holders of doctoral degrees (Zhou, 2015). According to China’s Ministry of Education, in 2016, 432,500 Chinese graduates returned to China, an increase of 60 percent over 2015 (China Daily, 2018, December 19, p. 16).
27. Freeman and Huang (2015) maintain that overseas training and networking has facilitated the closing of technology gaps.
28. Of the top 10 percent most cited publications, China’s share now stands at 14 percent (OECD, 2017).

29. An author publishing in the 68 highest rated scientific journals is given a score based on the number of articles to which the author contributed. This is known as the Fractional Index. This is then weighted with reference to disciplines to arrive at the Weighted Fractional Index. China's strength is greatest in chemistry, which contributes 61 percent of the total Weighted Fractional Index (Zhou, 2015).
30. China's STI system has suffered from fragmentation, research conducted by specialized institutes subject to top-down planning, and a lack of commercial orientation. Cultivating commercial linkages and changing mindsets have been slow processes (Klochikhin, 2013). Moreover, selection processes in academia have suffered from favoritism bias, with, for example, hometown ties to fellow selection committee members increasing the likelihood of selection to the Academies of Sciences and Engineering by 39 percent and subsequently distorting the allocation of university leadership appointments and research grant allocation (Fisman et al., 2018).
31. <https://www.nsf.gov/statistics/2018/nsb20181/report/sections/higher-education-in-science-and-engineering/international-s-e-higher-education>.
32. Leading the push to patent are Chinese companies such as Huawei, ZTE, Lenovo, Shenzhen Huaxing Optoelectronic, Hongfujin Precision Industry, Sany, BYD, Tencent, SMIC, Mindray Medical, and the Alibaba Group. In 2018, Huawei was the world's number one filer of international patent applications, <https://www.wipo.int/edocs/infogdocs/en/ipfactsandfigures2018/>.
33. The citing of Chinese patents by foreigners as an indicator of quality has been growing at an annual rate of 51 percent between 2005 and 2014 (Wei, Xie and Zhang, 2017).
34. <https://www.wipo.int/edocs/infogdocs/en/ipfactsandfigures2018/>.
35. Goldwind, include Ming Yang, Guodian, Envision, and CSIC. From: <http://nawindpower.com/top-10-wind-turbine-makers-for-2015-the-year-of-china>.
36. Nonservice/employee generated patents are less likely to be commercialized. Sixty percent of the utility patents and 56 percent of the design patents were of this sort (Prud'homme and Zhang, 2017). Although utility patents are easier to obtain and facilitated technological learning, their contribution to productivity is diminishing as Chinese industry moves up the learning curve.
37. The World Bank (2013) notes that research-industry collaboration is difficult to achieve even in high-income OECD economies. The authors cite firm-level evidence from Eastern Europe and Central Asia, which shows that while 75 percent of firms consider the acquisition of machinery and equipment to be an important channel for acquiring knowledge, less than 1 percent of firms felt the same way about collaborating with universities and public research institutes. However, evidence also shows that grants provided to consortia of firms and research entities can be an effective vehicle for incentivizing collaboration and generating more knowledge outputs through increased likelihood of patenting and commercializing products (Bruhn and McKenzie, 2017).
38. Although the shortage of qualified examiners and legal personnel with the requisite expertise persists.
39. Publication of a validating search report prior to the granting of a patent could be another step to raising quality.
40. This section is based on van Assche and van Biesebroeck (2017) and Misra (2017).
41. http://www.wipo.int/edocs/pubdocs/en/wipo_pub_943_2016.pdf.
42. See Rodrik (2006), Jarreau and Poncet (2012); Schott (2006); Wang and Wei (2010).

43. Similar results have been documented in countries outside of China. Halpern et al. (2009) find that a higher share of imported inputs increased the productivity of firms in Hungary, while Amiti and Konings (2007) obtain similar results for Indonesia. Goldberg et al. (2010) show that easier and cheaper access to imported intermediates in India led domestic firms to introduce additional product varieties, while Colantone and Crino (2014) find that a higher share of newly imported varieties in an industry raises the share of new domestic products in that industry in 25 European countries.
44. From: <https://www.bloomberg.com/news/articles/2020-01-18/germany-breaks-korea-s-six-year-streak-as-most-innovative-nation>.
45. The technology gaps clearly vary by industry and segment: some Chinese firms (for example, Alibaba, BGI) are among the top in their fields and McKinsey (2017) show that in 2016, China was in the global top three for venture capital investments across a range of leading technologies: fintech, virtual reality, autonomous driving, wearables, education technology, robotics and drones, 3D printing, big data, and artificial intelligence and machine learning.
46. From: <https://www.slideshare.net/seogwon/innovation-in-korea-20131023>.
47. From: <https://www.kiat.or.kr/site/engnew/index.jsp>.
48. From: <https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd#Agency>.
49. Such groups include a Leading Group on Science and Education, a Leading Group on Science and Technology System Reform and Innovation System Development, an Expert Consultation Committee on Innovation-driven Strategies, and other agencies.
50. Descriptions of STAR Metrics: <https://www.starmetrics.nih.gov>.
51. See, for example, <http://www.oecd.org/sti/inno/impact-assessment-public.htm>.
52. Regions where the labor force is ageing and shrinking more rapidly because of low fertility and out-migration will be more dependent upon gains in productivity to sustain growth although these gains will be harder to realize.
53. Markusen is referring more to industrial districts or clusters; however, her observation has a bearing on the success of an RIS.
54. Zhang, Wu, and Cooke (2010) note that until recently, China's technology zones were oriented more toward manufacturing than R&D.
55. Muro and Liu (2017) examine the growth of high-tech metro regions in the United States and show the dominance of the top 20. Liu (2013) shows that geographic proximity to universities has a positive impact on corporate patenting in China but not on the quality of patents.
56. Urbanization economies are defined in <http://www.oxfordreference.com/view/10.1093/oi/authority.20110803114851504>.
57. The servicification of manufacturing is now a well-known phenomenon and key to the profitability of many complex products.
58. Research universities and technology parks can encourage innovative entrepreneurial activity by setting up incubators and accelerators, as many have done. See, for instance, <http://www.scmp.com/week-asia/business/article/2085464/business-incubators-look-china-tech-worlds-next-big-thing>.

59. McCann and Ortego-Argiles (2016): “New entrepreneurial actions must be based largely on existing capabilities, skills-sets or knowledge-bases, such that diversification takes place in an incremental manner using existing knowledge and drawing on local strengths. These general principles highlight the importance of fostering development trajectories which are both connected to the existing knowledge ecology but at the same time attempt to re-orient the existing trajectories. In order to achieve this it is essential to ensure that local connections and synergies between institutions and actors are as strong as possible and policy actions draw on all of the available local resources in order to build both scale and concentration”.
60. <http://gra.org>.
61. An interesting finding reported by the report monitoring the EU’s Horizon 2020 Eurostars Program indicated that “The involvement of universities and research institutes did not prove to have a positive contribution to the approval of the applications; the highest success rates corresponded to consortia with only R&D SMEs, with a higher number of R&D SMEs, and with main partners located in the United Kingdom, France and Sweden”. (European Commission, 2017). This applies to all projects and not just those having to do with basic research, but it nevertheless raises a question regarding the contribution of universities in Europe.
62. See references cited in Cirera, Goni and Maloney, 2017. The division of research into basic and applied acquired traction after the publication of Vannevar Bush’s landmark study, “Science, the Endless Frontier”.
63. Acemoglu, Akcigit, and Kerr (2017) conclude that the flow of knowledge tends to be asymmetric, with patenting responding to upstream research.
64. Narayanamurti and Odumosu (2016, pp. 54-55) illustrate the interplay between the two categories of research by showing how the discoveries responsible for the award of six Nobel Prizes and Draper Prizes straddled invention and innovation. “The discovery of the transistor effect...relied on the invention of the bipolar junction transistor and led to the processors and chips that [are at the heart] of computers and cars to the invention of the integrated circuit... The invention of fiber optics combined with the materials engineering and invention of heterostructures made the physical environment and speed of global communications networks possible. In fact, the desire to improve the electrical conductivity of heterostructures led to the unexpected discovery of fractional quantization in two-dimensional systems and a new form of quantum fluid. Each of these could be classified as basic or applied research, but such classification elides the complexity and multiple nature of the research”.
65. From: <https://dc.mit.edu/sites/default/files/Future%20Postponed.pdf>.
66. Nanoscale catalysts could transform the production of energy. From: <http://www.futurepostponed.org/blog/2015/9/22/the-ultimate-clean-energy-strategyv>.
67. From: <http://www.futurepostponed.org/blog/2015/5/6/batteries>; this research entails probing the working of new chemistries using advanced nanotechnologies and exploring ways of manufacturing new batteries. Thus, research on storage cannot be neatly compartmentalized into basic, applied, and developmental.
68. From: <https://www.scmp.com/news/china/science/article/2189427/chinas-funding-science-and-research-reach-25-cent-gdp-2019>.
69. From: <https://www.aaas.org/programs/r-d-budget-and-policy/historical-trends-federal-rd#Agency>.

70. From: <https://www.nsf.gov/about/>.
71. If all the parts of the iPhone 6 were manufactured in the United States it would add about US\$100 to its price (Kakaes, 2016).
72. From: <https://www.insidehighered.com/news/2016/02/26/research-suggests-ways-western-universities-succeed-programs-china>.
73. This effort at mastering key technologies extends, it seems, to producing the metal ball casing of ballpoint pens. Early in 2017, the Taiyuan Steel announced that five years of research had finally resulted in a technological breakthrough. This SOE was now able to mass-produce the steel for the “ball socket containing the freely rotating ball at the tip of the pen” (Ng, 2017).
74. From: https://www.staufen.ag/fileadmin/HQ/02-Company/05-Media/2-Studies/STAUFEN.-studie-china-industrie-4.0-index-2015-de_DE.pdf.
75. A recent third-party assessment of Manufacturing USA by Deloitte concludes that it effectively addresses the gap between research and commercialization by connecting members who work in different parts of the R&D spectrum and by de-risking investments. According to the Deloitte report, participating institutes are achieving high degrees of network connectivity and strong member recruitment. The institutes are also becoming integrated into existing regional clusters and strengthening those clusters, thus tying innovation efforts to places with strong advanced manufacturing workforces and enabling R&D knowledge spillovers.
76. The Technology Research Institute of the Japan Society for the Promotion of Machine Industry is supporting the creation of applications for machine tools through ORiN (METI Journal 2015).
77. Fraunhofer, the National Academy of Technology Sciences, and the Industrie 4.0 platform published in 2016 a study titled “Competencies for Industry 4.0 – Qualification Needs and Approaches” that discusses both what enterprises can do to continually train and upgrade their workforce as well as how the German education system needs to adapt.
78. Finland’s government has taken a top-down approach, requiring mandatory teaching of coding to all students as part of basic education, although local municipalities have flexibility in implementing the program. Estonia has not made coding mandatory, but has taken a more bottom-up approach by encouraging PPPs to teach coding and robotics and to engage in other experimental initiatives to advance skills education. The United States has taken a “hybrid” approach of a top-down initiative from the Federal Government to fund the development of a bottom-up network of PPP digital skills vocational training programs for selected populations, including minorities and those needing job retraining.

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