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Upgrading of Technological Capability and Innovation Policy Transformation in China under a New Situation

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Abstract

Countries worldwide are actively pushing their innovation frontiers into the profound globalized innovation networks. China is entering into a new phase that experiences the profound transformation of the innovation systems and supporting policies, together with facing the accelerated technological innovation and emerging de-globalization trends. Improving the institution of innovation-driven development, as well as the quality and efficiency of innovation, are beneficial for China to integrate into the global innovation network and move towards the technological frontiers. This study analyzes the phases of the ongoing industrial innovation in China from the techno-economic perspective and proposes a multiple-factor framework to explore indigenous technological innovations. We suggest that the factors impacting technological upgrading and innovation capability are technological gaps, complexities of industrial ecology, the density of capital, and market need complexities under open competition conditions. These factors are necessary but not sufficient conditions for the success of cultivating the capability of technological innovations. The government must fulfill its roles adequately and effectively and pay more attention to the limits and focus of innovation policies. We propose that China's innovation policies need to be flexible towards the changing world's opportunities and challenges. China needs to boost its strengths towards an initiative and exploring role in the global innovation scene. Solid fundamental research and applications urgently need to support the layout of the upgrading of technological capabilities that bundled by greater openness and inclusiveness. Meanwhile, policies need to be transformed to guarantee equal benefits and greater tolerance to deliver an innovation-friendly system.

Keywords

technological capability; innovation policy transformation; techno-economic factors; China

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1. Introduction

As innovation becomes essential to a country's economic prosperity and social welfare in the face of developmental challenges, discussions abound in promoting technological progress and innovation through policies (Acemoglu *et al.*, 2006; Fagerberg, 2017). History has demonstrated the necessity of timely transformation in the innovation system and related policies when technologically backward countries maneuver to catch up with forefront countries in science and technology. To reach that end, a dynamic, mature, and vibrant innovation ecosystem is needed (Nelson, 1986; Freeman, 1987; Mark and John, 1996; OECD, 1999; Edquist, 2001; Dierks *et al.*, 2019). In the past few decades, China has made remarkable economic transformation achievements via technological advancements, innovation, and entrepreneurship. Its overall innovation strength or capacity is on a par with international evaluation standards, as its stretch towards leading developed countries keeps narrowing down (Cornell University *et al.*, 2019; Mu *et al.*, 2019). China is undergoing a profound transformation in its innovation policies.

Scholars who study the transformation of innovation systems put forward the basic framework of innovation policy evolution (Schot, 2014; Schot and Steinmueller, 2018), which is an evolving linear model phased by "Innovation Policy 1.0", "Innovation Policy 2.0" and "Innovation Policy 3.0." Accordingly, "Innovation Policy 1.0" features the path from invention to innovation and diffusion; "Innovation Policy 2.0" plays a recurring role in addressing problems and establishing the learning mechanism behind the generation, application, and interaction of innovations; "Innovation Policy 3.0" focuses on systematic transformation with a commitment to solving the socio-techno-economic problems induced by technological transformations (Schot and Steinmueller, 2016; Liang, 2017). Among the diversifying policy combinations dedicated to the transformation of innovations, "policy mix" has gained increasing prominence as an approach to generating and diffusing traditional technological innovations while driving the transformation of the entire socio-technological system (Weber and Rohracher, 2012; OECD, 2016; Kivimaa and Kern, 2016). Meanwhile, since the formulation of innovation policies often involves many different departments and institutions, the evolution of these departments and institutions' relationship is key to establishing effective innovation policy portfolios (Sun and Cao, 2018). Significant economic and social changes call for the cooperation and coordination among the makers of innovation policies (Kuhlmann and Rip, 2018). Practices from major developed countries have revealed five significant aspects of a sound innovation policy system: effective talent strategies and optimal skill allocations; a healthy, open, and fair business environment; sustained public investment in effective creation and diffusion of knowledge; increased participation and utilization of digital economy; and a mature governance and implementation system. In recent years, China's innovation policies have exceeded the phase needed to catch up with the first world. As changes take shape, more attention is being paid to the market mechanism, private enterprises, and the improvement of institutional conditions conducive to an efficient innovation system (Xie *et al*., 2013; Liu *et al*., 2017). Another highlight is the government's supporting role in ameliorating policy processes and tools (OECD, 2008; Chen and Naughton, 2016).

The world faces an unprecedented time of change, new technological revolutions, and re-globalization. Unknown factors such as COVID-19 are reshuffling the global political and economic order - established after the Cold War - towards a new balance. This process will profoundly change the paths and forms of technological innovations worldwide. Under this situation, China urgently needs to increase its pace in improving its innovation-driven development model, comprehensively upgrade the quality and efficiency of innovations, and intensify innovation's leading role in its economic transformation and upgrading. It

also needs to establish a more efficient and dynamic innovation system adaptive to international rules, with stronger motivation, initiative, and openness to be included in the global innovation network. Amid changing political and industrial conditions worldwide and nationwide, how will China match its innovation policies to phase transition? Answers to these questions are widely discussed and controversial.

This article summarizes China's major guidelines on innovation policies over the past 40 years and proposes a multiple-factor framework to analyze elements influencing China's industrial-technological innovations as a former "left-behind" economy. We elaborate on the transformative traits and priorities of China's innovation policies in its new phase of development. To sum up, China's innovation policy transformation should focus on solving four problems: (1) China needs to think and innovate initiatively instead of introducing ideas, while the relation between independence and interdependence needs to be addressed; (2) The government needs to break down barriers and open up a dynamic innovation environment; (3) Resources need to be allocated in a way that upgrades the technological capability; and (4) The openness of innovation policies should be further enhanced.

2. Review of China's Innovation Policies

The concept of "innovation policy" in its broadest sense has existed for a long time. It refers to public policies with an impact on innovation activities. Generally speaking, there are three types of innovation policies: mission-oriented policies, innovation-oriented policies, and system-level policies, each with its own historical contingency, policy motivation, and content (Elder and Fagerberg, 2017). In recent years, there are numerous operational definitions for innovation policy. However, to a large extent, it shares similar content with industrial policy, science policy, research policy, and technology policy. Lundwall and Boras defined it as "science, technology and innovation policy," or in other words, "the public policy on promoting the production, diffusion, and application of scientific and technological knowledge that the government can and has implemented in order to achieve national goals". With the reform and opening-up policy being carried out for more than 40 years, China's technological progress and innovation capacity have achieved immense success with an innovation policy system of broad coverage, diversified means, and multiple subjects. Its innovation policy system is visually presented here by several key categories (Table 1). For example, there are policies dedicated to industrial innovation, regional innovation, innovation elements, and innovation participants in terms of policy targets. China observes almost all types of innovation policy tools in the world. Due to its institutional uniqueness, China also owns more environmentally dependent innovation policies (Lyu *et al*. 2018).

As a representative "left-behind" economy of the 20th century, China has grown into an influential country of innovations, thanks to its improving innovation policy system and relevant institutional reforms. Specifically, China's innovation policy has transformed from science and technology policy into a comprehensive policy system covering all aspects of the innovation chain. Its policy tools have shifted from financial aid and tax incentives to institutional reform and innovation incentives among the general public. Since the 18th National Congress of the Communist Party of China, China has issued more than 200 policy documents to encourage innovation, of which nearly one-third are important policies directly promulgated by the CPC Central Committee and the State Council (Figure 1). These policies have changed from "supporting innovation subjects and encouraging innovation activities" to "creating an environment of innovation and cultivating an innovation ecology." The range of its policy tools has also become more inclusive and demonstrated some emerging patterns.

Table 1 China's major types of innovation policies by policy objectives

Policy Type	Policy Objectives	Policy Characteristics	Example
General Innovation Policy	Support research, development, and innovation activities	Correct market failure, and promote undiscriminating diffusion of knowledge	R&D for regional innovation and development
Institutional Innovation Policy	Establish a fair and friendly innovation environment	Correct system failure and implement reforms	Intellectual property policy; talent policy; standard policy
Social Development Innovation Policy	Promote social welfare and the diffusion of technology	Make up for the failure of market	Technological innovation in energy, environmental protection, and healthcare
Innovation Policy for Special Groups (Inclusive Innovation Policy)	Promote equal opportunities for innovation, entrepreneurship, and social development	Inclusiveness	Innovative activities targeted at small and medium-sized enterprises

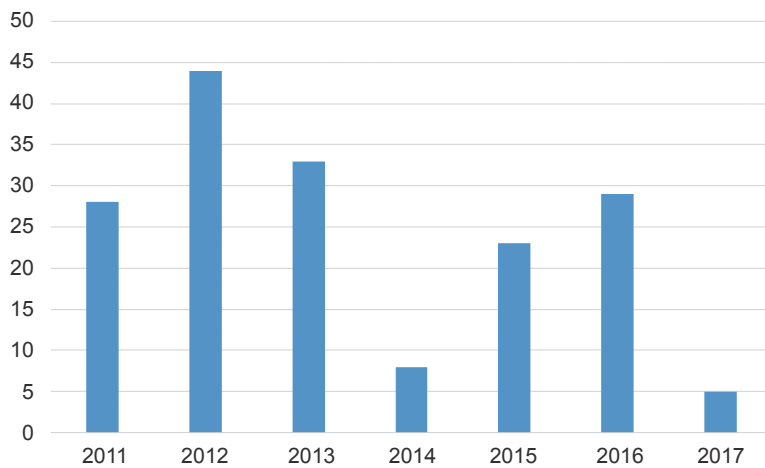

Fig. 1 Number of innovation policies in China

Source: Public data; Development Research Center of the State Council; World Bank Innovative China (2019)

First of all, China's policy tools have become more diversified. For example, R&D funding, special funds for technological transformation, tax reduction and tax exemption, public procurement, innovation vouchers, and other fiscal and tax means have been implemented to reduce innovation cost and to increase technological supply and market demand. Financial means to promote investment and financing, such as loan discount, guarantee, risk compensation, intellectual property pledge, and venture capital guidance fund, are prevalent in the market. Government supervision is also in place to guarantee quality standards and environmental protection.

Secondly, China's innovation policy supports a wide range of objects and participants. Scientific and technological investment policies are open to basic research and research programs. Subject-oriented policies encompass enterprise innovation policies, achievement transfer policies in universities and research institutions, and policies for innovation agencies, talent incubation, and interdisciplinary

integration. Industrial innovation policies, such as those supporting the development of high-tech service industries and high-end manufacturing industries, are also in place. Regional innovation policies, set up for national high-tech zones, indigenous innovation demonstration zones, innovative cities, national science technology innovation centers, innovation, and reform pilot zones, have taken effect. There are also innovation infrastructure policies established for national science centers, national laboratories, public technology platforms, science and technology sharing platforms, incubators, and maker space. Finally, innovation environment policies, financial policies, and institutional policies are all developed to support and coordinate the entire innovation system.

Thirdly, China's innovation policy concerns both the supply and demand sides of innovation. The past 40 years have witnessed more supply-side than demand-side policies, whereas now both sides are essential to solving market failure. The supply side, aiming at innovation capacity, addresses inefficiencies in technologies, talents, information, and management. On the other hand, the demand side addresses the imbalance between producers and consumers, establishes credits for new markets, lowers entry barriers of new technologies, and clears their development paths.

Fourthly, the market mechanism is playing a major role in China's innovation policy system. As early as 1985, the central government proposed reforming its funding system for scientific and technological development, opening up markets, lessening administrative power on innovation management, and fully empowering individuals to innovate via market mechanisms. In recent years, innovation policies have been carried out to answer that call. In 2014, the central government put forward a reformative document concerning funding for specific programs and scientific plans. In 2015, the document "Opinions on Deepening Systematic Reform and Accelerating the Implementation of Innovation-driven Development Strategies" was published. In 2016, the "Guidelines on Innovation-Driven Development" came out, marking the transfer of administrative power from the government to the market as a venue for resources and incentive for innovation, decision-making, and organizational cohesiveness.

3. The New Situation and Challenges Faced by China

3.1. Deeply integration into globalization, and promoting open innovation as well as coopetition with a higher level

An essential experience in China's technological catch-up and innovation in the past 40 years is the organic synergy of outside knowledge, technologies, and indigenous innovation. Technological import and open innovation are important ways for local enterprises to close the technological divide and generate innovation from imitation (Fu *et al*., 2016). Nevertheless, globalization has entered a challenging and complex new phase. Traditional international economic and trade rules and international governance mechanisms have fallen behind new problems resulting from globalization. Recent years frequently bear witness to "black swan" incidents in global finance and economy, public health, and public security; de-globalization trends, global trade frictions, and geopolitical disputes have been triggered. Rules and regulations for global competition are being rewritten to lay out a new world political and economic landscape. Globalization will unquestionably move on from "Era 2.0" to "Era 3.0", but major retrogression risks in the short and medium-term loom large.

Similarly, the globalization of scientific and technological innovation is facing a series of severe challenges, especially because policies for scientific and technological innovation are highly susceptible to international rules (Xiong and Ma, 2020). Innovation and globalization are continually dueling and pushing history forward in twists and turns. Knowledge and information have no borders. The cross-

national flow of international talents, technologies, and capital will still be the tenet of our time. However, as technological competition intensifies, and the "hi-tech" race continues among nations, the transfer and replacement of global science and technology centers will only accelerate.

Additionally, a series of practical challenges, such as national security, non-tariff barriers, and government power games, intensifies. Some countries implement high-tech export controls or technology embargos, namely, for national security concerns, which aggravate technical trade barriers and restrict cross-border flow. The game between big powers and ideological discordance also gave rise to geopolitical competition, leading to further "fragmentation" of the global innovation network. The impact of international rules on science and technology innovation policies is also intensifying. As global interests re-balance, challenges posed by major public health events, energy, environmental sustainability, and new technology ethics will make fair competition and coordinated development a mandate for global innovation and governance.

Meanwhile, the global governance system is seeking a more equitable transition towards the coexistence of multilateral and plurilateral systems. Specifically, in recent years, the rapidly narrowing gap between the "North" and the "South" has changed the context and meanings of "center" and "peripheral" countries. It will be inevitable for emerging economies to integrate themselves into the global innovation network and play a more significant role.

Global pandemics, network security, digital security, bioethics, terrorism, and other non-traditional security issues are becoming increasingly menacing for humanity, posing unprecedented changes to security situations worldwide. As the ongoing COVID-19 pandemic continues to deteriorate public health and safety in many countries, it has also forced countries to rethink the place of a pandemic, plague, and biological safety in their security system. Network and emerging digital technology development also bring about new national security issues represented by network attacks, privacy leakage, and intelligence theft. According to the report "Global Trends 2035" issued by the European Parliament, more and more individuals, countries, and organizations will have mastered advanced network intrusion skills by 2035. New network threats will emerge endlessly. The task of network protection will not be limited to preventing confidential information theft; anti-subversion and anti-destruction will also become the foci of national security efforts. Countries with a backward digital economy will be at a disadvantage in intelligence collection, information security, privacy protection, and digital currency. Digital sovereignty will become a new space for a race among great powers after their fight on the land, sea, and air. In addition, controversial new biotechnology developments, such as cloning, synthetic biomedicine, gene editing, and neural technology, also face risks of blurring ethical and security boundaries. Conclusively, non-traditional competitions among countries will intensify the complexity of national security maintenance and the fight over geopolitical dominance. The capacity to cope with non-traditional security challenges will gradually symbolize a country's leadership and international status.

3.2. Adaptation to rapid technological changes, uncertainty and be ready for reform

A new round of technological revolution led by emerging digital technologies accelerates productive and industrial revolutions, especially as technological innovations become ever more disruptive. New technologies, such as cloud computing, big data, the Internet of things, artificial intelligence, and blockchain, have undergone significant breakthroughs to be applied in virtually all sectors of the economy and the society. As the new round of technological revolution goes on hand in hand with the expansion of information technologies born from the Internet, telecommunication has become the pillar for big data,

the Internet of things, artificial intelligence, and other forms of information technology. Biotechnology and material technology have also made advancements into the social sphere, becoming secondary to the new technological revolution. Also, emerging industries such as the green economy and low-carbon industry are booming in response to calls for sustainable development.

The interdisciplinary and inter-technological integration trend is also leaping forward, exerting a greater impact on societies' economic growth. On the one hand, new information and communication technologies promote hybridization across industries and fields through digitization and smart technology, transforming industries at an astonishing speed. Rapid development in fields like artificial intelligence, virtual reality and augmented reality, human-computer interface, sensors, and physical information systems has made co-penetration and deep integration of the cyberspace and the physical world possible. On the other hand, information and communication technologies also promote the diffusion of knowledge and innovation, offering a powerful means for scientific research, disciplinary innovation, and paradigm shifts in science. Technological reform and breakthroughs are on the outburst.

Technological progress and system reconstruction have opened up the scene for global innovation, characterized by diversity, market autonomy, and grassroots spirit. The progress of digital technology also deepens the "inter-connection" of the world, making the flow of innovation resources highly flexible, adaptable, and accessible (OECD, 2019). The threshold for participation in innovation is considerably reduced. Anyone could now innovate in a more elaborate industrial organization system and social division of labor. Technologies, researchers, and laboratories are no longer essential to innovation; any user, any participant on an open platform, could freely create, crowd-source, coordinate, and lead innovations. As more innovations are generated from the grass-root level, public-private partnerships in R&D will become routine.

The new technological revolution will also reshape the international economic structure, triggering ups, and downs. Several countries have issued innovation strategies and policies to seize time for future economic and technological advances. After introducing the *American Innovation Strategy* in 2009, the United States again carried out two revisions in 2011 and 2015, laying out its blueprint for long-term economic growth and competitiveness through scientific and technological innovations, with stress on investing in the rudimentary elements of innovation and creating an inductive economic and policy environment for entrepreneurs. The EU also put forward Europe 2020, with adherence to intelligent, sustainable, and inclusive growth, and building the EU into an "innovative alliance" within the next ten years. To summarize, technological breakthroughs and the large-scale application of emerging digital technologies will fundamentally change the basis, organizational model, and traditional economy forms, pushing global economic structures on a fast track to change and a new order. Countries that seize the opportunities of the new technological revolution and industrial transformation will assume leading roles in innovation and economic dominance, while those left behind will gradually decline in the new round of the international competition.

3.3. Venture to the innovation frontier with strength and quality

Scientific and technological innovation in China has entered a new phase. The profound transformation, development, and upgrading of China's economic society have laid out new innovation requirements. After years of "catching up," China has become a leading country in science, technology, and innovation. Its capacity for innovation is increasingly characterized by high quality. According to the World Intellectual Property Organization's (WIPO) 2020 global innovation index, among the 141 countries included in the evaluation, China's comprehensive ranking jumped to the 14th in 2020 after entering the top 25 for the first

time in 2016. Its performance in business maturity, knowledge, and technology output is highly competitive among other leading countries. Many of China's science, technology, and innovation indicators revealed its unique advantage in scale, and in some areas of innovation, it has even reached the world's top level. At present, China's overall R&D expenditure ranks second globally, accounting for 2.18% of its GDP and exceeding the average of OECD countries. The total number of its R&D personnel claimed the world's top spot at number one, and the number of its approved patents has been on top of global ranking consecutively since 2011. Scientific papers published in international journals ranked second globally, after the United States. However, the proportion of basic research investment in its entire R&D expenditure remains low, far behind major developed countries. The quality of its scientific and technological output still needs to be enhanced. Its disadvantages are apparent in the citation rate of scientific papers, patent quality, and other indicators. Although its capacity to turn scientific discoveries into products is on a par with Europe, there is much room to catch up with the US. Compared with other countries of leading innovation strengths, China's institutional environment, human capital, scientific and technological infrastructure, and creative output are far from being satisfactory. China's scientific and technological development has gone through consecutive stages of equipment import, technological transformation, and product imitation. As long as it keeps the edge in patented R&D and engineering capabilities, keeps consolidating its basic research capacity and creativity, a holistic ecosystem of innovation will soon arrive. Despite the changing external environment, China is dedicated to continuously enhancing its scientific and technological strengths, improving the quality of innovation, achieving the long-term goal of leaping over the middle-income trap, and entering the forefront of innovative countries.

As China transforms its economic priority from high-speed to high-quality, its mode of development, optimization of economic structures, and changing growth dynamics have generated higher scientific and technological innovation requirements. Its economic growth now hits a bottleneck where the volume of its environmental resources can no longer sustain a model for traditional large-scale production. Its edge in catching up with the developed world by merely winning over resources and labor capacity is no longer valid. Much of its opportunities now lie in innovations that stimulate economic structure optimization and industrial upgrading for a sustainable economic and social development model.

Innovation brings new ideas and new technologies, dramatically promotes export growth, generates business opportunities, stimulates economic growth and structural optimization, and improves employment. Currently, China's economy continues to face greater downward pressure. Stable economic growth will become a primary task in the future. More importantly, under the background of intensified de-globalization, the global industrial and supply chain are facing massive reconstruction. It is imperative to establish a new type of international scientific and technological partnerships. In that regard, China should boldly deepen its reform, open up markets and investment opportunities, and stimulate the populace by encouraging "mass entrepreneurship and innovation" to expand its potential for growth and disruptive technologies.

4. A Framework for Explaining the Phase-transition of China's Technological Innovation and Relevant Major Factors

China's scientific, technological, and industrial development is a process of technological learning and catching up. Years of fast development allowed China to emerge as a counterpart of countries it tried to take after, owing to its capacity for innovation and manufacturing. China has proven itself successful in advancing industrial and technological progress in two aspects: (1) Long-term, sustained investment and

learning in science and technology, which laid the foundation for its industrial output; (2) Opening up to technologies and resources, which increased its exposure to the world's most advanced technologies and equipment. "Import, absorption, and re-innovation" were the keynote of China's strategies and policies for science and technology for a long time.

4.1. Innovation transformation: from integrated innovation to component innovation

After decades of industrial development, most industries in China are now equipped with the capacity to integrate major technologies. However, one major problem is that most industries are manufacturing-oriented and, at best, assemblers of basic materials, components, and spare parts. The ability to provide high-quality and highly reliable products for increased value and competitiveness is yet to be cultivated. This underscores one challenge to be addressed in China's industrial, technological upgrading.

Compared with the technological upgrade for whole machines or entire systems, intermediate products' upgrading offers special thinking opportunities. Broadly speaking, the upgrading of intermediate products like key components requires more intricate technology and a more complex market environment. To achieve the fundamental technological knowledge and skills in upgrading components, enterprises should acquire the necessary materials, research backup, and skillsets over the long run for sustainable competitiveness. Even if such assets are accessed through reverse engineering of prototypical products, it is hard for copycat products to meet the demand of high-end markets in terms of reliability and quality, as they are missing the R&D elements. Also, as whole product systems often adopt more stable and reliable component parts to maximize overall performance, the capacity to deliver trustworthy component parts will determine a manufacturer's place in the market. As world markets continue to open up through globalized supply chains, secondary quality products may quickly lose the race (Table 2). Therefore, China's domestically made components can only supply its medium and low-end machinery markets for intermediate technological upgrade needs. It is ironic to think that its whole-machine products are procured in the world's high-end markets.

Table 2 Comparison of technological innovations in integrated products and component parts

Main Features	Systematic Integration or Architectural Innovation	Innovations in Component Parts
Product	End product (whole machine)	Intermediate products (component parts)
Technology	Open procurement and production according to market demand and product positioning	Determine the stability and reliability of the whole product
Knowledge and Innovation	Explicit knowledge based on the understanding and application of technology and experience; innovation in technology and experience	Tacit knowledge based on the understanding and application of the scientific principles; innovation based on knowledge accumulation
Industry	Global procurement of intermediate products	Fierce competition worldwide
Market	Direct consumer needs; government procurement	Downstream user needs (whole machine assemblers)
Technological Access	Technological imitation, indigenous R&D, and transnational R&D	Indigenous R&D, M&A, cooperation, and transnational R&D
Requirements	Quality of component parts and industrial infrastructure	Solid scientific and technological assets
Examples	High-speed rail, nuclear power, large aircraft	Semiconductor, industrial software

As demonstrated, both the technological and market requirements for component parts and intermediate products require solid foundations in science and technology on the national level. The upgrading of technology and the manufacturing capacity of upstream industrial chains is also essential. In addition to technical capacity, long-term accumulation of stable and reliable market credit is also necessary for a place in the global high-end market.

4.2. Factors affecting technological innovation upgrading

History shows that economic factors are the main driving force for a country to upgrade industrial technology and innovation capability. In other words, domestic enterprises can obtain more profits via upgrading of the value chain. The market incentive is the fundamental driving force of technological upgrading and innovation. In the absence of market incentives, technological innovation initiated by the government and its policies will not counter the negative effect of competition. Throughout the past 70 years, major changes in the global political climate have significantly impacted China's path for technological development. Their development was openly embraced by globalization.

To motivate upgrading technological innovations, both the market and the government can play a role. Government procurement provides the initial demand and trial-and-error opportunities for indigenously developed technological products. The government can use fiscal and tax incentives to stimulate market demand for innovative products. However, in a decentralized and competition-driven market, due to a lack of user incentives, technological products initiated by the government frequently lose to the products of higher quality, reliability, and performance, as the latter is sought after by consumers.

The success of technological catch-up in specific industries depends not only on preferential investment and incentive policies, but also on other industrial, market, and technological factors. Identifying the key factors from complexities helps accelerate breakthroughs and the industrialization of core technologies and helps to understand policy limitations. Analyzing China's practice in its industrial and technological catch-up on conditions of the open and competitive socialist market economy, we identified four major factors affecting technological upgrading and local technological innovations, which are technological gap, complexities of industrial ecology, the density of capital, and consumer/market demand complexities (Figure 2).

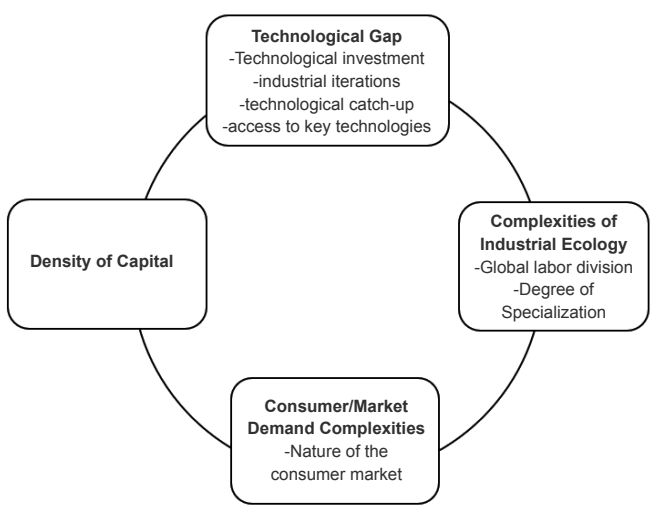

Fig. 2 Main factors influencing indigenous innovation

Notably, these factors are necessary, if not sufficient, conditions for indigenous innovations' success. The success of indigenous innovations often depends on these conditions. However, even if all the conditions are met, it is not necessarily a guarantee that the indigenous innovation will succeed, because it is also affected by other complex factors.

4.3. Technological gap

Technological gap refers to the dynamic changes in the technological "catch-up" of an underdeveloped country with developed countries. It determines the technological feasibility of indigenous innovation to turn into products. The technological gap is affected by the bridge between international and domestic progress on certain technologies but differs from domestic technological development variations. Several constituting factors include:

(1) Level of science and technology. Represented by the amount of funding and research resources, a country's scientific and technological foundation determines its capacity for research and development and the ability to absorb new advancements. A lack of knowledge and talents in relevant technological fields will significantly hinder the pace of progress. One of the crucial reasons for China's backwardness in basic fields like materials and key components is the lack of long-term investment in materials science and technology. The scientific and technological foundation also determines how fast China could catch up and even surpass other countries. However, as knowledge is a cumulative practice, it is difficult to achieve "leapfrog development" in science and technology. Breakthroughs in frontier technology must be supported by fundamental research. Under the condition of opening up, the improvement of a country's science and technology level can be obtained from increasing domestic investment in science and technology and personnel training, and appropriate global cooperation forms to obtain maximum resources. However, science and technology's cumulative effect determines that no matter what kind of technology is acquired, the support for technological learning and development still depends on long-term investment in science and technology. Nonetheless, the government faces a dilemma in allocating resources: on the one hand, long-term investment and funding are needed; on the other hand, not all fields of science and technology could be covered due to resource and budget limitations. The traditional "spray and pray" strategy would only maintain a low technological delivery level instead of advancement.

(2) Industrial iterations and technological maturity. In areas where technological progress is slowing down and reaching maturity, the technological gap is likely to narrow down. For example, China is more successful in catching up with traditional industries and mature high-tech industries like power transmission infrastructure, mainly because these are already mature technologies developed abroad. However, in areas of rapid technological upgrading, to catch up is more challenging. For example, China has been able to catch up with international advances in integrated circuit technology but is now falling behind quickly.

(3) Access to key technologies from outside. Access to technologies refers to opportunities for technological learning. It includes acquiring foreign key technologies, especially tacit knowledge, such as technical training through formal and informal venues. Acquiring knowledge from the outside is a vital channel for technological learning and development, and it is still necessary and essential for developing countries to acquire knowledge from developed countries. Indeed, the more a country has fallen behind, the more urgent it is to acquire learning from outside sources. Unfortunately, tacit knowledge like experience, skills, industrial secrets, and patents cannot be shared openly and significantly limit the speed at which the technological gap can be narrowed. Under the new global climate, access to key technologies that have been effective but not in line with international practice is significantly reduced, meaning that

the opportunities for learning such knowledge are relatively reduced.

(4) Technological catch-up. Whether a country can surpass its counterparts in the technological race is also affected by its backup volume in the necessary resources, such as research talents. The chance for technological catch-up will soon evaporate if the determining resources are not in place.

4.4. Density of capital

The density of capital determines the major players in indigenous innovations and their products and the commercial feasibility of investment. In industries with huge R&D investment, a higher density of capital, and longer investment cycles, technological catch-up is a hard race. It is difficult for both enterprises, and the government to acquire initial funding, not to mention continuous investment. Limited by funding restraints, the scope and strength of government support for technological innovation is lamentable. There are also higher opportunity risks for the government. The risks lie in two aspects:

(1) Technological risks. Indeed, there are risks and uncertainties in the development of science and technology. The smaller the range for technological options, the greater risks, and uncertainties there are. The emergence of disruptive technology will also lead to technological transformations that generate higher opportunity costs.

(2) Market risks. Technological success is not equal to product success nor business success. Successful technology can lead to failed products, and successful products would not always sustain a successful business. These are the rules of market competition. For countries that strive to catch up, huge investment risks and market risks lie ahead despite the best investment capacity at hand. Such risks also make it difficult for the government to make investment decisions. For an enterprise to win in the market competition, innovation is the necessary, if not sufficient, condition of its business cost. The government faces considerable opportunity cost for its investment decisions, which necessitates its non-intervention in the market. Naturally, the government will invest in more fundamental research activities beneficial to creating and maintaining standard technologies. As a result, emerging technologies face greater pressure to source indigenous funding.

In terms of fundamental research, scientists, instead of the government, decide which technologies to invest in. However, nation-wise, government strategies for investment in frontier technologies differ. Some governments rely on national strategies for decision-making, some rely on R&D potentials (such as Denmark), whereas others adopt a mixed approach. Still, decisions are heavily leaned towards mature technologies to lower risks for opportunity cost. In international practice, government investment is mainly restrained by policy orientations instead of evaluations of profits, risks, and costs.

4.5. Complexities of industrial ecology

The complexities of industrial ecology are reflected in industrial division and platform effect. Longer industrial chains and finer labor division inevitably make indigenous innovation more challenging to achieve and encompass the whole industry. For example, in the integrated circuit industry, an immense amount of technical details, patent barriers, professional training, and labor division are involved in the extended industrial chain from material assembly to packaging. A country's capacity to master a whole industrial chain requires a high technological comprehension level and dexterity, which is often an aspiration. Therefore, such industries are often highly globalized, and countries are competitive in only one or two manufacturing aspects. Last but not least, there is also the platform effect, which applies to software products such as operating systems.

4.6. Market demand complexities

The nature, scale, and demand complexities of the product market impact the success of products derived from indigenous innovations. Policies that come out as feedback to the demand of challenges need to consider the complexities of market demand to conceptualize demand conditions (Boon and Edler 2018).

(1) Nature of the market. The nature of the market determines how difficult it is for indigenous innovation products to enter the market and how much profits could be generated. In China, it makes a difference whether innovative products are procured by the government or sold in the general open market. The government procurement of a particularly innovative product is sometimes mandatory. Under this circumstance, products do not encounter the "peer pressure" to be of better quality or lower price, and can easily meet the demand. However, highly innovative products face a higher entry threshold with fiercer competitive pressure for quality, price, and functions in a general market.

(2) Market scale. Market scale determines whether innovative products could be profitable. Even in the relatively easy government market, demand is vital for an enterprise that relies on the government for its livelihood, not to say competitiveness. In the past, some enterprises had to undertake heavy financial burdens after delivering products into a small government market, unable to sustain stable demand.

Conclusively, the above factors are key to the success of indigenous innovated products. It is imperative for the government to play a rational and efficient role in guiding innovation through its policies. Of course, it is easier for indigenous innovation to succeed under the ideal market and technical conditions. Under other conditions, highly competitive stress may lead to entrepreneurial failure. The manufacturing of such high-end products is also highly specialized and technically complex, requiring an extremely intricate division of labor. These industries also face fierce pressure for competition globally. In that regard, the government should emphasize the importance of enhancing the technological basis and open innovation networks in devising policy incentives (Table 3).[1]

Table 3 Factors influencing China's technological innovation upgrading

	Major Changes	**Constraints**
Technological Gap	Opportunities for technological transformation upon new technological revolution	The scientific and technological foundation in some key fields is weak, and the gap is widened; higher policy compliance requirements limit access to innovation for traditional technologies
Industrial Ecology	Commercialization and ecological innovation of digital economy; digitization of manufacturing industry	Dependent on innovation paths, scale effect, the global division of labor, and coordination between upper and lower supply chains (*i.e.*, industrial ecology prefers to integrate processing and manufacturing lines based on different EDAs supported by a strong database)
Density of Capital	The threshold for capital is lowered due to the digital economy	Higher density of capital in advantageous industries in developed countries
Consumer/Market Demand	Increased demand for supply chain toughness	International rules for government procurement

[1] From the perspective of technology and economy, the conditions for realizing indigenous innovation in nuclear power are better. It includes a single government market, a small technology gap, and relatively simple industrial ecology. Therefore, centralized investment in this area would solve technical problems.

5. Suggestions for China's Innovation Policy Transformation in the Future

5.1. From "shortboard" to "long board": solid foundation and strengthen advantages

Given the challenges for development both at home and abroad, China's innovation policy must be transformed to address new requirements and tasks (Table 4). In terms of strategy, policy focus needs to shift from fixing weaknesses to boosting strengths in innovation. The government should proactively encourage and support fundamental research, frontier technologies' R&D. It should also dedicate to creating a beneficial, inclusive, and fair environment for competition and cooperation. In the key areas of science and technology planning and organization, intellectual property protection, R&D transformation at the university level, government procurement, and talent incubation, more flexible and reasonable policies need to be devised to reflect the changing demand of domestic and world situations.

Table 4 Suggestions for China's innovation policy transformation

Content	Goals
Transformation in Scientific Development Strategies	"catching up" and "building advantage" "fixing weaknesses" and "boosting strengths"
Transformation in Policy Conceptualizations	Transform from competition to cooperation, from quantity to quality, from economic development to socio-economic development
Transformation in Policy Types	Policies need to be beneficial, operational, and inclusive
Transformation in Government Roles	Offer more basic and institutional services via platforms
Transformation in Policy Processes	Both macro and micro levels of policies need to coordinate to bring out the role of the market in encouraging innovation
Transformation in Implementation Mechanism	Support and implement fundamental research, frontier technologies, and coordination across departments via key technological and organizational mechanisms

In the future, China's scientific and technological development should give consideration to technology "catching up" and advantage building. The strategic core of maintaining technological advantages is to put forward national policies that are "visionary, practical, and inclusive." Accordingly, China needs to define its key technological areas for long-term development and innovation, and boldly take the initiative of furthering its advantages in some technologies instead of being on the defensive in others.

The development of national science and technology should "look to the future." In today's world, the scientific and technological competition among major countries is oriented towards future predominance. China's current focus on national science and technology investment will determine its future edge in certain sectors. Once one country's leading edge is established, it is very difficult for other countries to surpass in the short run. China's former development path of catching up with developed countries via "technological learning" has duly addressed its past lack of the fundamental knowledge and skills required by innovation.

Again, the fields of forming local technological advantages must be supported by solid fundamental research and applications. The integration of theories, applications, and product development is key

to delivering such edgy fields. Scientific plans and funding management, to fulfill this goal, need to be implemented hand in hand to sustain each joint of the innovation process. In theoretical and technical research, specific "knowledge gaps" need to be breached as these are also lessons left unlearned from the last round of traditional innovation. In other words, "strengthening advantages" and "fixing weaknesses" are complementary. From there, efforts shall be put into furthering advantages. In all, the strategy of playing out sectional technological advantages shall concentrate on investing in fundamental research.

In the long run, focusing on developing certain technological advantages will constitute China's overall strategy for development. This is a practical move beneficial to consolidating research foundations. However, openness and inclusiveness are also necessary. Openness is embodied in opening up basic research and cutting-edge technology research programs for world-class scientists. Only by accumulating universal knowledge and wisdom will China's scientific and technological progress be genuinely global. Access to scientific and technological resources should also be offered to the greater public so that large and medium-sized enterprises will equally participate in national science and technology programs. More generous support is also needed for interdisciplinary breakthroughs.

5.2. Suggestions and implications for policy transformation

Innovation policies should be more competitive and inclusive and give full play to institutional support's fundamental role. The priority is to increase the effectiveness and benefits of inclusive innovation policies. The scope of inclusive policies also needs to be expanded and avoid simply setting policy thresholds based on business sizes, profitability, and the number of patents. For popular and effective policies, entry bars should be further lowered to amplify their effect. In the same spirit, policies that only benefit a part of the general population need to phase out. Inclusive policies are an antidote to developmental uncertainties as they reduce malicious competition and the "bidding out" effect of big players in the game. Next, inclusive policies should also consider the innovative and entrepreneurial efforts of the "less advantaged" groups, such as small and medium-sized businesses, enterprises in underdeveloped areas, and entrepreneurs with challenging physical abilities. This is also a wise approach to social justice. Vulnerable groups will be supported by special R&D investment, technological promotion, tax incentives, training and entrepreneurship promotion. Finally, a fair, competitive, and friendly institutional environment will offer innovators the peace of mind to continue innovating.

Most importantly, intellectual property rights should be duly credited and protected to generate sustainable income for innovators. Relevant policies on talent incubation and training will further encourage brain flow across sectors. As long as the evaluation standards for innovation are carried out coherently and consistently, innovators will face fewer barriers in the market and make positive contributions.

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