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National Innovation Development Index: A Cross-country Comparison of Innovation Development Performance

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Abstract

Innovation development has received increasingly more attention from academia and policy-makers. The policy-making for promoting it heavily relies on evidence provided by measuring national innovation development. This study tries to build a bridge between innovation development measurement and policy-making. The literature shows that there is very limited theoretical and methodological research on measuring national innovation development. This paper proposes a national innovation development index (NIDI) for measuring the performance of national innovation development by integrating the definition of innovation from five perspectives and the definition of development from four perspectives. The NIDI consists of five sub-indexes, science and technology development sub-index, innovation condition development sub-index, industrial innovation development sub-index, social innovation development sub-index, and green & low-carbon development sub-index, which is measured by the composite sub-index approach. This paper uses the NIDI methodology to investigate 40 countries based on the panel data from 2006 to 2015, which helps classify countries into three categories including leading, advanced and catching-up countries. The cross-analysis between sub-indexes of the NIDI brings new insights into the competitive advantage and disadvantage, which helps governments to choose more specific policies to overcome shortcomings resulted in the poor performance of sub-indexes of the NIDI so as to improve their innovation development performance systematically. Besides, the findings in this article indicate that the level of economic development in a country is to a large extent determined by the level of national innovation development.

Keywords

national innovation development; national innovation development index; cross-country comparison

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1. Introduction

As one of the main driving forces for economic and social development, innovation has received increasing more attention from both academia and policymakers. Schumpeter points out “Nor will the mere growth of the economy, as shown by the growth of population and wealth, be designated here as a process of development” (Schumpeter, 1934, p:63). “Development in this sense is then defined by the carrying out of new combinations (Schumpeter, 1934, p:66)” and shows five cases of the new combinations, namely: “(1) The introduction of a new good or of a new quality of a good. (2) The introduction of a new method of production. (3) The opening of a new market. (4) The conquest of a new source of supply of raw materials or half-manufactured goods. (5) The carrying out of the new organization of any industry.” The cases above show that the development in Schumpeter's definition mainly focuses on the economic perspective of development, and implies some linkages with the product technology, process technology, marketing innovation and organization innovation. However, he did not discuss the relationship between innovation and development.

Innovation development means a development way driven by innovation, which concerns the effectiveness, efficiency, and efficacy of innovation activities. Chinese scholar Mu points out that “Innovative development refers to innovation-driven development, which embodies the result of innovation promoting economic and social development. It also reflects the evolution of science and technology and innovation capacity itself” (The Center for Innovation and Development of Chinese Academy of Sciences, 2009, p21). Mu defines the innovation from five perspectives, and points out that innovation is a complex process of value creation, including the creation of scientific value, technological value, economic value, social value and cultural value (Mu and Fan, 2011). In his definition, the activity of value creation is diversified in nature and dominated by different innovation stakeholders. For example, the research institutes and universities are dominant in the creation of scientific value, while enterprises are dominant in the creation of economic value. Traditional understanding on development pays great attention to the quantity growth, the structural optimization and the quality improvement of economic development, while he emphasizes the integration of the economic development and social development as well as environmental development. Therefore, he redefines the innovation development from four perspectives, namely: the science and technology development, the economic innovation development, the social innovation development and the environmental innovation development. The economic innovation development means the innovation-driven economic development, related to product and process technology development and industry organization innovation as well as marketing innovation. The social innovation development means innovation-driven social service development, related to establishing higher quality, lower cost and wider coverage public service system by using new IT and AI. The environmental innovation development means innovation-driven environment development, related to environmental protection and environmental restoration with supports of technological innovation and government organization innovation.

From the perspective of science, technology and innovation (STI) policy research paradigm, we have experienced the transformation from science and technology policy research paradigm to innovation policy research paradigm, and presently to innovation development policy research paradigm. The first generation of STI policy research paradigm arose in the early 1960s when many OECD countries established their ministries of science and technology, indicating the institutionalisation of government support for science and technology. The second generation of STI policy research paradigm emerged in the early 1990s when national innovation system in the context of globalization gradually started to become the theoretic frame of STI policy with a view to improve system efficiency of innovation, and strengthen international competitiveness. The third generation of STI policy research paradigm started in the early 2010s when global and local development challenges play increasingly more important role in STI policy, the future development vision and the science and technology development trend as well as the innovation capacity become the dominant factors in the STI policy process. Schot and Steinmueller (2019) point out that Science, technology and innovation (STI) policy is shaped by persistent framings that arise from historical context. Two established frames are identified as co-existing and dominant in contemporary innovation policy discussions. A third frame linked to contemporary social and environmental challenges such as the Sustainable Development Goals and calling for transformative change is identified and distinguished from the two earlier frames. Transformation refers to socio-technical system change as conceptualized in the sustainability transitions literature. The nature of this third framing is examined with the aim of identifying its key features and its potential for provoking a re-examination of the earlier two frames. Innovation measurement has also experienced three generations in terms of STI policy research paradigm, from focusing on the knowledge production activities (science and technology policy), the knowledge production and its commercialization activities (innovation policy), to focusing on the development vision-driven innovation activities (innovation development policy). Therefore, the first-generation innovation measurement mainly concerns R&D activities from the perspective of input and output of R&D activities and tries to describe the nature of R&D in detail with some indicators such R&D expenditure and publications as well as patents. The second-generation innovation measurement mainly concerns the input & output and impact of innovation activities and tries to describe the nature of innovation in detail with indicators related to R&D expenditure, publications and patents as well as economic effectiveness. The third-generation innovation measurement concerns the impact of innovation-driven development from four dimensions including the science and technology development, the economic innovation development, the social innovation development and the environmental innovation development.

Literature review shows that there are many studies on measurement of innovation performance in a broad sense, mainly related to the first- and second-generation innovation measurements. The European Innovation Scoreboard (EIS) and the Global Innovation Index (GII) are two representatives of innovation measurements. The ESI provides a comparative assessment of the research and innovation performance of the EU Member States and the relative strengths and weaknesses of their research and innovation systems (European Innovation Scoreboard 2019 —Methodology Report, p3). ESI's indicator system consists of four main types of indicators, and ten innovation dimensions, capturing in total 27 different indicators. Four main types of indicators include (1) the Framework conditions, (2) the Investments, (3) the Innovation activities, and (4) the Impacts. It is worthwhile to point out that EIS mainly focuses on the economic value of innovation. Therefore there are lots of indicators related to enterprise innovation, and no indicators related to social impacts of innovation. The Global Innovation Index (GII) (2019) provides detailed innovation metrics for 129 economies, which covered represent 91.8% of the world's population and 96.8% of the world's GDP in 2019. The GII consists of the Innovation Input Sub-Index and the Innovation Output Sub-Index. The overall GII score is the average of the Input and Output Sub-Index scores. The Innovation Input Sub-Index is comprised of five pillars that capture elements of the national economy that enable innovative activities: (1) Institutions, (2) Human capital and research, (3) Infrastructure, (4) Market sophistication, and (5) Business sophistication. The Innovation Output Sub-Index provides information about outputs that are the result of innovative activities within economies. There are two output pillars: (6) Knowledge and technology outputs and (7) Creative outputs (Cornell University et al., 2019, p9).

There are very limited studies related to the third-generation innovation measurement because of limited innovation development policies in practice. In 2006, the Chinese government promulgated the Outline of National Medium- and Long-Term Plan for Science and Technology Development (2006-2020) and put forward the ambitious goal to become an innovative country by 2020. Thereafter, the Chinese government has issued a series of policies to implement the Outline so as to promote science and technology and innovation since 2006. The Central Committee of the Communist Party of China proposed to implement National Innovation-driven Development Strategy so as to promote efficient allocation and integration of innovative resources, and pool the wisdom and strength of the whole society into innovation development in 2012. The Central Committee of the Communist Party of China and the State Council jointly issued Some Opinions on Deepening the Reform of Institutional Mechanisms to accelerate the Implementation of Innovation-driven Development Strategy in 2015, and the Outline of National Innovation-Driven Development Strategy in 2016. Besides, Chinese government has selected 8 regions (Guangdong, Anhui, Sichuan, Shanxi, Beijing-Tianjin-Hebei, Shenyang, and Wuhan) to implement the overall innovation and reform experiments related to new policies and regulations with a view to promote regional innovation development. All the innovation policies in practice show that the changing development philosophy has a profound impact on the innovation policy and finally resulted in the transition from innovation policy to innovation development policy since 2012. Therefore, it is necessary to evaluate and monitor the performance of global innovation development in general and Chinese innovation development in particular so as to provide evidence for revising and making innovation development policy in the context of implementing Innovation-driven Development Strategy in China.

Mu et al. (2010) developed a national innovation development index with five sub-indexes, including: the industrialization development with more consideration on resource-saving and environment-protecting, the informatisation development, the urbanization development, the education and health development, and the science and technology and innovation development, which concerns not only the social & economic development driven by innovation, but also the development of science and technology and innovation development[1]. Besides, the recently emerging concept of "transformative innovation" is to some extent similar to the connotation of innovation development, and emphasizes that innovation has significant social and environmental impact.

[1] Mu began to study the innovation development in 2003 and the innovation development measurements with the establishment of the Center for Innovation and Development of Chinese Academy of Sciences (CASCID) in December 2006. He published on behalf of the CASCID the China Innovation Development Report in 2009. The NIDI was firstly published in China Innovation Development Report 2009 by Science Press.

However, there is no unified definition of the transformative innovation policy in academic circles. Some defines the transformative innovation policy as “system redesign and culture change in the way people think about products and services”, and “improvements to optimize existing systems of knowledge”. It is necessary to develop a rational indicator system to measure the performance of nation innovation development instead of the national innovation performance so as to provide critical evidence for improving STI policies.

This study tries to formulate an STI policy ecosystem with a view to improve innovation development policy in a sustainable way. Firstly, it is to develop a new national innovation development index (NIDI) from a multi-dimensional perspective on the basis of our understanding on innovation development as well as the last NIDI in 2009 (The Center for Innovation and Development of Chinese Academy of Sciences, 2009). Secondly, it is to establish a bridge between the STI policymakers and the NIDI focusing on value-creation by redefining the innovation development and carefully selecting indicators with policy significance.

The rest of this paper is structured as follows. Section 2 builds the measurement framework of the national innovation development. Section 3 outlines the methodology. Section 4 offers an analysis of the NIDI empirical results. Section 5 concludes and discusses the results as well as the limitations of the study.

2. Measurement Framework of National Innovation Development Index

2.1. Measurement framework

The design of innovation development measurement is based on the understanding of innovation development. Different from the conventional understanding of economic perspective of innovation, innovation development is more concerned with the effects of innovation-driven economic, social as well as environmental development. Mu has given a comprehensive definition of innovation development[2] in The Report on Innovation Development in China 2009 (The Center for Innovation and Development of Chinese Academy of Sciences, 2009; see also Mu et al., 2010). Mu pointed out that innovation development not only includes the development of science and technology, but also reflects innovation-driven economic, social as well as environmental effects. The connotation of this concept concerns not just the profits of innovation but also the directionality of innovation, whether it leads to the ‘good’ or ‘bad’ consequences to the society and environment. This concern is echoed with the concept “responsible research and innovation” described as a process that takes into account effects and potential impacts on the environment and society. The recently emerging concept of “transformative innovation” also recognizes social and environmental impact of innovation, especially environmental impact.

[2] In December 2003, Mu put forward the idea of “innovation development” in the report of “Innovation Driving Development, S&T Shaping the Future - Strategic Thinking on Science and Technology Development in China” (Chinese Academy of Sciences, 2005). In December 2006, National Development and Reform Commission of Peoples’ Republic of China and Chinese Academy of Sciences jointly established the Center for Innovation and Development (CID). Mu acted as the founding director of CID. As the earliest academic institute carrying out research on innovation development in China, the CID has published “The Report on Innovation Development in China 2009” in 2009.

This study develops a new national innovation development framework (Fig. 1) based on a new understanding of innovation development and Mu's definition of innovation value from five perspectives (Mu and Fan, 2011). Innovation development is multi-dimensional and encompasses many aspects, ranging from science and technology development to economic, social and environmental development. Compared with the NIDI proposed by the Center for Innovation and Development of Chinese Academy of Sciences in 2009, the new analytical framework of the NIDI in this paper pays much more attention to environmental impact of innovation.

This new framework consists of five sub-indexes (Fig. 1). The first is science and technology development sub-index, which measures the level of scientific and technological value creation in a country. There is no doubt that innovation development is to a large extent determined by hard/soft infrastructure, knowledge stock, and education, and thus, the second is the innovation condition development sub-index in a country. Industrial innovation development sub-index, as the third sub-index in the framework, presents the performance of innovation-driven economic development, mainly focusing on manufacturing and service sectors, in a country. The fourth, namely social innovation development sub-index, presents the performance of innovation-driven social development in a country. Lastly, the green & low-carbon development sub-index, as the fifth sub-index, presents the performance of innovation-driven environmental development in a country.

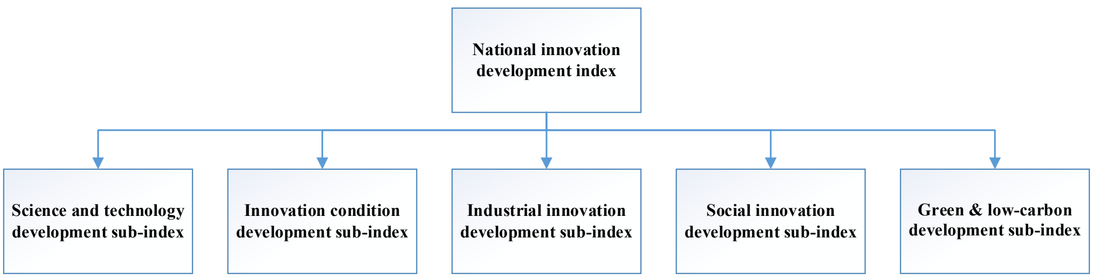

Fig. 1 The analytical framework of national innovation development

2.2. *Indicator system*

Innovation development means the innovation-driven development, which concerns the effectiveness, efficiency, and efficacy of innovation activities (Mu et al., 2010). This means that innovation development emphasizes the level of the effectiveness, efficiency and efficacy of innovation-driven development. Hence, only ratio indicators are considered in this framework. There are three rules to follow when choosing measurable indicators. Firstly, the connotation of the sub-index can be clearly described and well presented by proxy indicators. Secondly, the indicators should be comparable among selected countries. Thirdly, the indicators' data should be available in the observed period. Table 1 presents the indicator system for national innovation development index (NIDI).

The science and technology development sub-index presents the level of the effectiveness, efficiency and efficacy of science and technology activities, related to science and technology inputs and outputs. The intensity of science and technology input including personnel and expenditure is the precondition for science and technology development, and thus we choose R&D expenditure per million people and researchers per million people as the proxy indicators. The density of

Table 1 The indicator system for national innovation development index

Index	Sub-index	Indicator	Source
National innovation development index	Science and technology development sub-index	R&D expenditure per million people	WB
		Researchers per million people	WB
		SCI, SSCI, and A&HCI papers cited per million researchers	WB and WOS
		Patent grants (resident) per million researchers	WB and WIPO
		PCT patent applications per million researchers	WB and WIPO
		Charges for the use of intellectual property (receipts) as a percentage of GDP	WB
	Innovation condition development sub-index	Individuals using the Internet as a percentage of population	WB
		Patents in force per million people	WB and WIPO
		Government expenditure on education as a percentage of GDP	WB
	Industrial innovation development sub-index	The export of high-tech products as a percentage of manufactured exports	WB
		Value-added in services as a percentage of GDP	WB
		Employment in services as a percentage of total employment	WB
		GDP per employee	WB
	Social innovation development sub-index	Urban population as a percentage of total population	WB
		Public health expenditure as a percentage of GDP	WB
		Public health expenditure as a percentage of total health expenditure	WB
		Life expectancy at birth	WB
		Tertiary school gross enrollment	WEF
	Green & low-carbon development sub-index	GDP per unit of energy use	WB
		GDP per unit of CO_2 emissions	WB
		CO_2 emissions per capita	WB

Note: WB is World Bank (data are from World Development Indicators); WOS is Web of Science (data are from InCites database); WIPO is World Intellectual Property Organization (data are from Intellectual Property Statistics); WEF is World Economic Forum (data are from Executive Opinion Survey).

science and technology output including publications and patents reflects the level of science and technology development. The numbers of publications and patents have some limitations in innovation measurement, such as the fact that they cannot represent the quality of innovation output. However, publications and patents are still the often used proxy indicators in terms of international comparability and data availability. Thus, this study chooses SCI (Scientific Citation Index), SSCI (Social Sciences Citation Index), and A&HCI (Arts & Humanities Citation Index) papers cited per million researchers, patents granted (resident) per million researchers, PCT (Patent Cooperation Treaty) patent applications per million researchers and charges for the use of intellectual property (receipts) as a percentage of GDP as the proxy indicators for science and technology output measurement.

The innovation condition development sub-index presents the level of the effectiveness, efficiency and efficacy of innovation condition development. The sub-index presents the density of the infrastructure condition, knowledge stock, and educational condition. Information and communication technology infrastructure provides the necessary support for innovation development, so we choose individuals using the Internet as a percentage of population to show the level of innovation infrastructure in a country. Patents in force represent knowledge accumulation in a country. Thus, we choose patents in force per million people to represent the level of knowledge stock. Education condition is the foundation for the science and technology talent development, and thus, we choose government expenditure on education as a percentage of GDP to reflect the educational effort of a country.

The industrial innovation development sub-index presents the level of the effectiveness, efficiency and efficacy of innovation-driven industry development. The sub-index measures the level of economic value creation of innovation in a country. It emphasizes the dominant function of science and technology in industrial development, especially in advanced manufacturing and productive service sectors. We choose the export of high-tech products as a percentage of manufactured exports. For the productive service sector, due to the limitation of data availability, we have to choose value-added in services as a percentage of GDP and employment in services as a percentage of total employment to reflect the innovation development in the service sector. The indicator GDP per employee shows the industrial development level in a country.

The social innovation development sub-index presents the level of the effectiveness, efficiency and efficacy of innovation-driven social development. The sub-index involves the development of public service sectors such as education, healthcare, transportation and public security. Due to the limitation of data availability, this study has to choose indicators related to education and healthcare. Besides, we have to choose urbanization as an indicator to reflect the level of public service sector development in general. We choose the tertiary school gross enrollment to express the ubiquitous degree of higher education, and choose three indicators to reflect the level of public healthcare sector, including the public health expenditure as a percentage of GDP, the public health expenditure as a percentage of total health expenditure, and the life expectancy at birth.

The green & low-carbon development sub-index presents the level of the effectiveness, efficiency and efficacy of innovation-driven environmental development, related to the energy consumption, the emission reduction and the environmental remediation. The sub-index embodies the concept of sustainable development as well as the harmonious relationship between humans and nature. This sub-index reflects the transformation of the innovation-driven economic development pattern from quantity growth to high-quality development in a country. Therefore, the indicators related to the energy consumption, the emission reduction and the environmental remediation, are very important. However, due to the limitation of data availability, we have to choose three indicators to measure the green & low-carbon development, including the GDP per unit of energy use, the GDP per unit of CO_2 emissions, and the CO_2 emissions per capita. The GDP per unit of energy use and the GDP per unit of CO_2 emissions reflect the industry structure and the level of innovation-driven industry development in a country. The CO_2 emissions per capita is to measure the degree of environmental pollution. The higher the value of it, the worse the environmental performance is.

3. Measurement Methodology

To calculate the national innovation development index, there are five steps to follow: data collection, dealing with missing data, normalization, weight selection, and index calculation.

Data collection. This study selects 40 countries[3] as the sample with the consideration of the cross-county comparability and data availability. These 40 countries include major members of OECD, G20, and BRICS. The total GDP of these 40 countries accounted for more than 85% of the total GDP of the world in 2015. The data of this study are from the World Bank, the Web of Science, and the World Intellectual Property Organization.

Dealing with missing data. There are some ways to deal with missing data. First, if data are not available at the beginning of the time series, this study estimates them using data trends over the next 5 years. Second, if data are not available at the end of the time series, this study estimates them using data trends from the previous 5 years. Third, if data for a year-in-between are not available, this study uses the 2-year averages to estimate the value in the intermediate year.

Normalization. In order to make the indicators of different measure units comparable, the measured values of 21 basic indicators in 40 countries are standardized with reference to the estimated values in 2020 year. The reason of choosing 2020 year as the benchmarking year is that the 2020 year is the milestone year for China's innovation development. China's government wants to become an innovation-oriented country in the year. This study contains both positive indicators and negative indicators. The positive indicators are those with higher scores and better performance. Conversely, the negative indicators are those with higher scores and poorer performance. Normalization makes the indicators easy to compare, and all the indicators are normalized into the [0, 100] range.

Z_{ijt} (i=1, 2, …, 40; j=1, 2, …, 21; t€[2006, 2015]) is the value of country i of indicator j in year t.

maxZ_{ijt} (i=1, 2, …, 40; t€[2006, 2020]) is the maximum value of indicator j in 2006–2020 among 40 countries.

minZ_{ijt} (i=1, 2, …, 40; t€[2006, 2020]) is the minimum value of indicator j in 2006–2020 among 40 countries.

$\overline{Z}_{ijt}$ (i=1, 2, …, 40; j=1, 2, …, 21; t€[2006, 2015]) is the normalized value of country i of indicator j in year t.

The positive indicator follows equation (1):

$$\overline{Z}_{ijt} = \frac{Z_{ijt} - \min Z_{ijt}}{\max Z_{ijt} - \min Z_{ijt}} \times 100 \qquad (1)$$

The negative indicator follows equation (2):

$$\overline{Z}_{ijt} = \frac{\max Z_{ijt} - Z_{ijt}}{\max Z_{ijt} - \min Z_{ijt}} \times 100 \qquad (2)$$

Weight selection. In this study, the weight is based on expert judgment. In order to obtain the rational weight, this study allows experts with rich experience and better understanding about

[3] The countries are Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, India, Ireland, Israel, Italy, Japan, Malaysia, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russia, Singapore, Slovakia, South Africa, South Korea, Spain, Sweden, Switzerland, Thailand, Turkey, the United Kingdom, and the United States.

national innovation development, to assign weights for each indicator and sub-index. Then, we calculate the average weights. The expert judgment is an experience-based method which can give a set of weights reflecting the policy orientation.

Index calculation. This study ranks selected countries after calculating each sub-index and the NIDI with the specific weights.

y_{ikt} (i=1,2,…,40; k=1,2, 3, 4, 5; t€[2006, 2015]) is the value of sub-index k of country i in year t.

W_j (j=1, 2, …, 21) is the weight of indicator j.

Using equation (3), we obtain the score of each sub-index.

$$y_{ikt} = \sum W_j \overline{Z}_{ijt} \quad (3)$$

Y_{it} (i=1,2,…,40; t€[2006,2015]) is the value of the NIDI of country i in year t.

W_k (k=1,2, 3, 4, 5) is the weight of sub-index k.

Using equation (4), we obtain the score of the NIDI of country i in year t.

$$Y_{it} = \sum W_k y_{ikt} \quad (4)$$

4. Measurement Result Analysis

4.1. Rank analysis

The scores and ranks of the NIDI of 40 countries in 2006 and 2015 are shown in Fig. 2. Compared with developing countries, developed countries, especially some small-size developed countries,

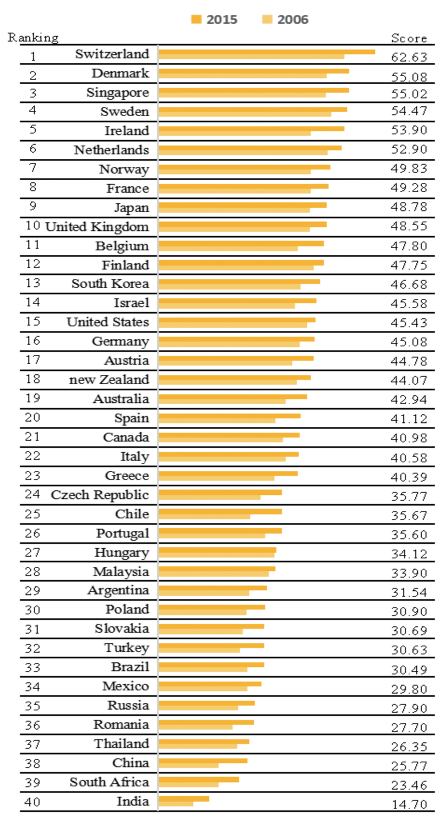

Fig. 2 Ranks of national innovation development index

perform better in terms of the NIDI scores. In 2015, Switzerland was ranked at the first among 40 countries, and its NIDI score (62.63) is significantly higher than the second-ranked country. Besides, Denmark, Singapore, Sweden, and Ireland had a higher NIDI score above 50, and are ranked into the top five countries. There is a small gap among other 5 countries (the Netherlands, Norway, France, Japan, and the United Kingdom) of the top 10 countries in the NIDI score. Their NIDI scores range from 48.55 to 49.83. The countries ranked at the 11th ~20th are Belgium, Finland, South Korea, Israel, the United States, Germany, Austria, New Zealand, Australia and Spain, which are developed countries. In contrast, some developing countries perform poorly in the NIDI performance. BRICS members, Brazil, Russia, China, South Africa, and India, are ranked at the 33rd, 35th, 38th, 39th and 40th, respectively.

The top 10 countries in the average annual growth rate of NIDI in the period of 2006-2015 are China, India, South Africa, Chile, Romania, Turkey, Slovakia, Ireland, Spain, and Russia (see Fig. 3). China ranks first with 4.36%, while, other two BRICK countries, India and South Africa, also step into the top 10 with an average annual growth rate of 4.23% and 3.33%. However, the average annual growth rate of most developed countries is relatively low. For example, the average annual growth rate of the United States, Japan, and Germany is 0.63%, 1.17%, and 1.07% respectively.

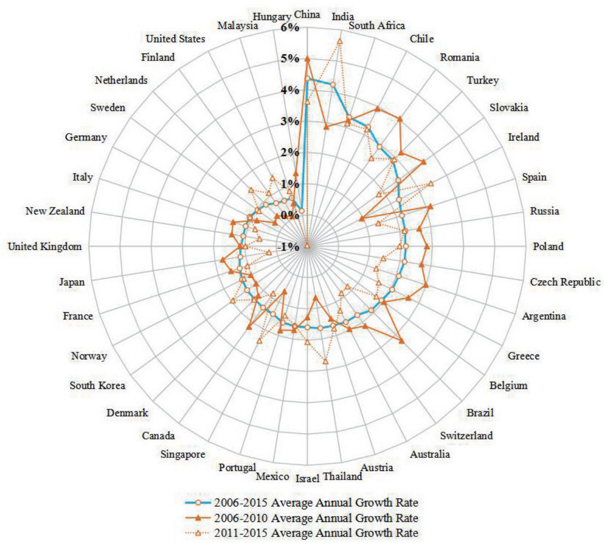

Fig. 3 Average annual growth rate of national innovation development index

Note: The countries in the figure are sorted clockwise by the value of average annual growth rate of 2006-2015.

Some countries have a big imbalance in terms of the innovation development performance shown by the NIDI and sub-indexes. Table 2 further presents the ranking results of the NIDI and its five sub-indexes in 2006 and 2015.

The rank of some countries is high in the NIDI score, while the rank of them in one or several sub-indexes is low. Taking Switzerland as an example, it can be seen that the rank of social innovation development sub-index is the 23rd, although its NIDI score is ranked at the first in 2015. The rank of the NIDI score of Singapore is the 3rd, however the rank of the science and technology development sub-index and the social innovation development sub-index of it is the 20th and the 21st.

Table 2 Ranks of national innovation development index and sub-indexes

Country	National innovation development index		Science and technology development sub-index		Innovation condition development sub-index		Industrial innovation development sub-index		Social innovation development sub-index		Green & low-carbon development sub-index	
	2015	2006	2015	2006	2015	2006	2015	2006	2015	2006	2015	2006
Switzerland	1	1	1	1	2	3	4	6	23	23	1	1
Denmark	2	4	4	6	4	1	11	10	3	3	3	9
Singapore	3	5	8	20	19	17	1	1	21	28	13	3
Sweden	4	2	3	3	3	2	14	14	2	1	4	4
Ireland	5	8	10	19	1	5	2	4	28	24	2	6
Netherlands	6	3	2	2	17	13	9	5	1	7	26	24
Norway	7	7	13	12	7	6	7	11	8	5	25	21
France	8	9	19	15	11	11	3	8	12	11	8	7
Japan	9	10	7	5	8	12	17	13	4	8	29	27
the United Kingdom	10	11	17	14	10	9	8	7	10	10	6	14
Belgium	11	15	12	13	16	19	13	18	5	4	22	29
Finland	12	6	6	4	6	4	21	12	7	6	27	34
South Korea	13	13	5	9	5	8	12	9	19	18	36	33
Israel	14	17	15	10	18	20	10	17	18	14	21	25
the United States	15	12	9	7	14	10	6	2	16	19	39	40
Germany	16	14	14	8	13	14	15	15	14	16	23	26
Austria	17	18	11	11	20	18	19	20	17	20	11	16
New Zealand	18	16	21	21	9	7	24	24	6	2	28	23
Australia	19	19	16	18	15	16	16	21	9	9	38	38
Spain	20	22	23	22	26	26	23	27	13	12	7	15
Canada	21	21	18	17	12	15	18	19	15	13	37	39
Italy	22	20	20	16	36	28	22	23	22	15	5	11
Greece	23	24	26	25	21	29	20	22	11	17	18	18
Czech Republic	24	27	24	26	22	27	27	26	20	21	32	36
Chile	25	28	22	24	32	32	37	36	24	29	17	10
Portugal	26	26	25	28	23	22	31	29	27	25	9	8
Hungary	27	23	27	23	34	21	26	16	30	26	14	20
Malaysia	28	25	36	38	25	23	5	3	37	36	33	28
Argentina	29	29	37	33	24	37	36	35	25	22	19	17
Poland	30	32	30	30	27	24	35	37	29	27	31	31
Slovakia	31	33	32	31	30	25	32	34	31	33	24	30
Turkey	32	34	31	32	35	38	39	38	26	31	16	5
Brazil	33	31	38	36	28	30	25	30	35	34	12	2
Mexico	34	30	35	35	33	31	29	25	34	35	15	12
Russia	35	35	34	29	29	35	28	33	32	30	40	37
Romania	36	37	33	34	39	33	38	39	33	32	10	22
Thailand	37	36	40	40	38	36	33	28	36	37	30	19
China	38	38	29	37	37	39	30	32	38	38	34	32
South Africa	39	39	28	27	31	34	34	31	39	39	35	35
India	40	40	39	39	40	40	40	40	40	40	20	13

The rank of some countries is low in the NIDI score, while the rank of them in one or some sub-indexes is high. For example, the rank of Malaysia's NIDI is the 28th, while the rank of the industrial innovation development sub-index is the 5th. The rank of Brazil's NIDI is the 33rd, while the rank of the green & low-carbon development sub-index is the 12th.

4.2. Classification comparative analysis

To further illustrate the performance differences in the sub-indexes among countries, we choose three typical groups of countries to compare respectively in terms of the average and maximum values of the 40 countries in 2015. The first group consists of the top five countries in the NIDI ranking, namely, Switzerland, Denmark, Singapore, Sweden, and Ireland, as shown in Fig.4. These countries are small-size high-income economies, and have an obvious advantage in innovation development level. The second group consists of five large-size high-income developed countries with a relatively higher NIDI ranking, namely, France, Germany, Japan, the United Kingdom, and the United States as shown in Fig. 5. These countries are usually known as strong economies in science, technology and innovation, which have a profound impact on the evolutionary direction of the global innovation development pattern. The third group consists of BRICS countries as shown in Fig. 6. The BRICS countries are large-size developing countries, and those countries' innovation development will affect the evolution of global innovation development patterns. Those three categories of countries have a major difference with each other.

The first-group countries have outstanding advantages in most of sub-indexes. The maximum value of five sub-indexes is determined by the value of sub-indexes in this group's countries. For example, the maximum value in the industrial innovation development index, green & low-carbon development index, science and technology development index, innovation condition development index, and social innovation development index of the 40 countries is determined by the calculated values of Singapore, Switzerland, Ireland and the Netherlands respectively. The performance of most sub-indexes in the second group is above the average of 40 countries except for that of the green & low-carbon development index in the United States, Japan and Germany. In contrast to the maximum value, the performance of science and technology development index in these developed countries does not present an obvious advantage as expected. The BRICS countries have an obvious disadvantage in all sub-indexes' performance in contrast to the average of 40 counties. Except for the green & low-carbon development index in South Africa, the sub-index values of the BRICS countries are below the average of 40 countries. This means that the performance of their NIDI and sub-indexes obviously lag compared to developed countries, although some BRICS countries as emerging economies have got increasing science and technology outputs.

4.3. Cluster analysis

According to the NIDI scores, we cluster the 40 countries into three groups with reference to the level of GDP per capita. The group I is considered as the leading countries in innovation development, which consists of countries with the top NIDI score and the top GDP per capita, including Switzerland, Denmark, Singapore, Sweden, Ireland, the Netherlands and Norway. The group II is considered as the advanced countries in innovation development, which consists of countries with the high-level NIDI score and the high-level GDP per capita, such as the United States, Japan, Germany, and France. The group III is

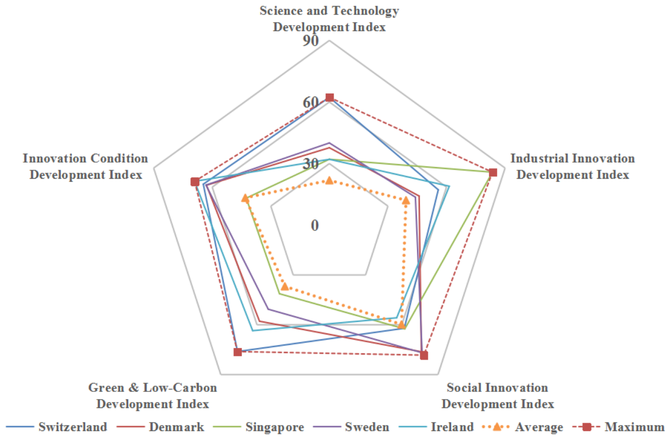

Fig. 4 The sub-index comparison of NIDI of small-size developed countries in 2015

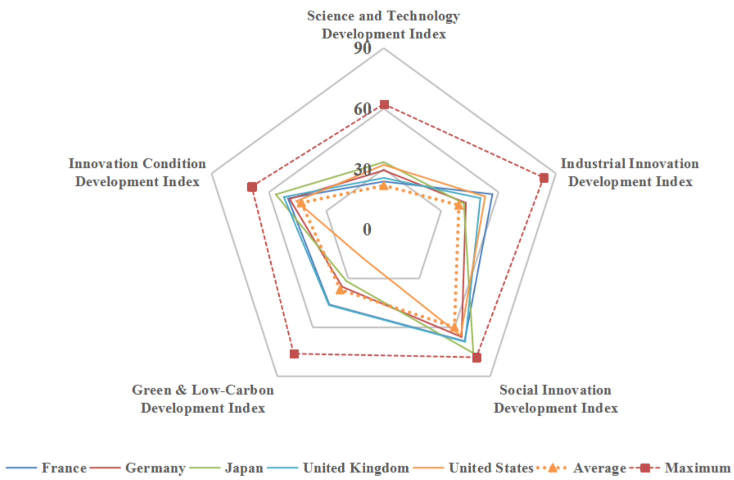

Fig. 5 The sub-index comparison of NIDI of large-size developed countries in 2015

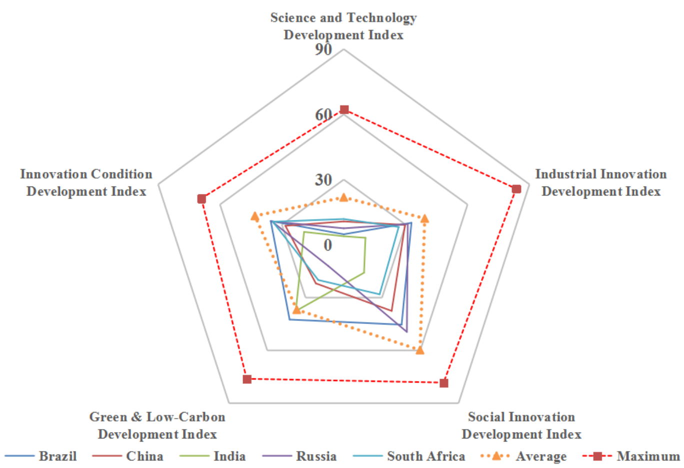

Fig. 6 The sub-index comparison of NIDI of BRICS countries in 2015

considered as the catching-up countries in innovation development, which consists of countries with the low-level NIDI scores and the low-level GDP per capita, including the BRICS countries.

Based on the balanced trend line drawn according to the power law function relationship between the NIDI score and the level of GDP per capita (see Fig. 7), the 40 countries are divided into upper and lower parts. The balanced trend line helps to identify the economy-specific performance in innovation development. For countries in the upper part, the relative level of the NIDI is better than that of GDP per capita in 40 countries. The part below the line is the opposite. Some countries appear on the line, which means that their NIDI scores match their level of GDP per capita. Countries below the line should take great efforts on the improvement of innovation development by making use of their economic advantage. Besides, Fig. 7 shows that the level innovation condition development index score (The bubble area in Fig. 7 is determined by the innovation condition development index score.) has an effect on the distribution of 40 countries in this figure. Those countries with the high NIDI score and the high level of GDP per capita are located in the upper-right corner around the balanced trend line.

The cross-comparisons in two different sub-indexes can display the comparative advantage and disadvantage among countries. This paper draws a two-dimensional graph based on the science

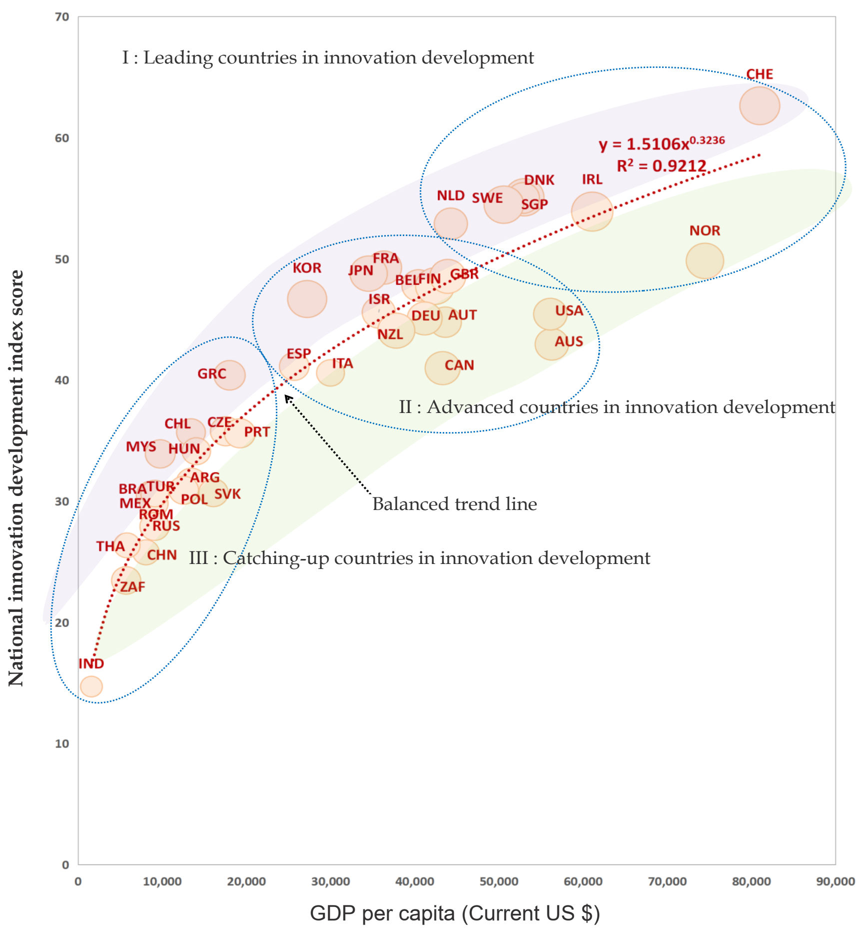

Fig. 7 National innovation development index score and GDP per capita

Note: The bubble area presents the score of innovation condition development sub-index.

and technology development index rank (on the horizontal axis) and the industrial innovation development index rank (on the vertical axis) (see Fig. 8). The number in parentheses in the figure is the rank difference between the industrial innovation development index score and the science and technology development index score. The nine-quadrant graph helps to visually presenting the categories of the 40 countries with the combined consideration of the science and technology development index score and the industrial innovation development index score.

The diagonal line is a balanced line of the position of 40 countries in terms of the two sub-indexes. Most countries lie around this line. Countries on the line have same ranks in the science and technology development index score and the industrial innovation development index score, including Australia, Spain and Canada and Slovakia. Countries below the line have a higher rank in the science and technology development index score than the industrial innovation development index score, including 21 countries such as Switzerland, Denmark, Austria and New Zealand. The rank difference of some countries such as Chile, Sweden and Finland are large, which is above 10. Those countries have an obvious advantage in the science and technology development index score than he industrial innovation development index score. Countries above the line have a higher rank in the industrial innovation development index score than the science and technology development index score, including 15 countries such as Brazil, Mexico and Russia. Countries close to the line are basically balanced countries in terms of two sub-indexes, such as Germany, Belgium and China. Countries far away from the line are imbalanced in terms of two sub-indexes, such as France, Malaysia and Brazil.

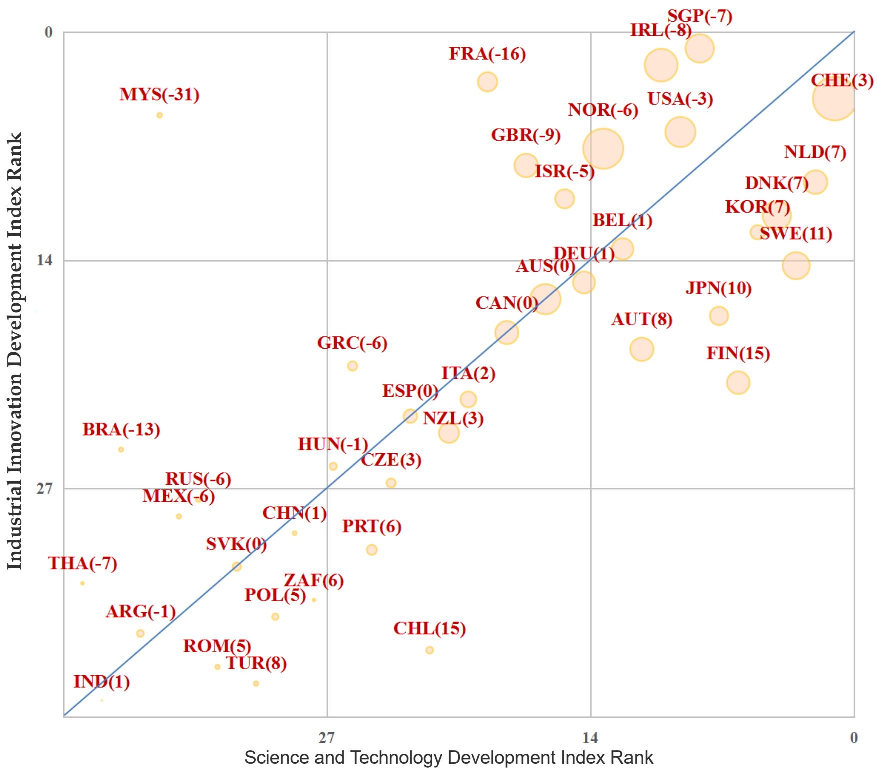

Fig. 8 Cross-analysis between science and technology development index rank and industrial innovation development index rank (2015)

Note: The bubble area presents the standardized GDP per capita (2015 current price)

Besides, we find that GDP per capita is closely related to the distribution of 40 countries in the two-dimensional graph. We find most countries with a high GDP per capita are in the top-right corner, while most countries with a low GDP per capita are in the bottom-left corner. Countries in the top-right corner are those with good performance in both science and technology development and industrial innovation development, most of which are developed countries, such as Switzerland, Singapore, and the United States. This finding implies that the level of both the industrial innovation development index and the science and technology development index to a large extent influences positively the level of economic development.

This paper also draws a two-dimensional graph based on the science and technology development index rank (on the horizontal axis) and the social innovation development index rank (on the vertical axis) (see Fig. 9). The number in parentheses in the figure is the rank difference between the social innovation development index score and the science and technology development index score. The nine-quadrant graph helps to visually presenting the categories of the 40 countries with the combined consideration of the science and technology development index score and the social innovation development index score.

The diagonal line is a balanced line of the position of 40 countries in terms of the two sub-indexes. Most countries lie around this line. Countries on the line have same ranks in the science and technology development index score and the social innovation development index score, including Germany and

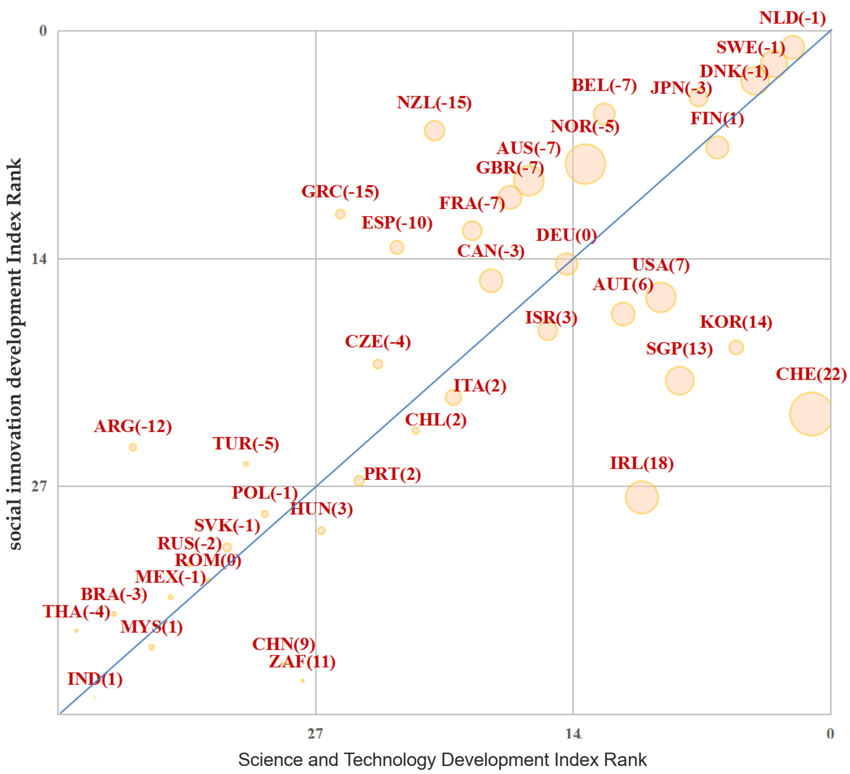

Fig. 9 Cross-analysis between science and technology development index rank and social innovation development index rank (2015)

Note: The bubble area presents the standardized GDP per capita (2015 current price)

Romania. Countries below the line have a higher rank in the science and technology development index score than the social innovation development index score, including 16 countries such as Finland, India, the United States, China, Malaysia, Chile, Italy, Portugal and Hungary. The rank difference of some countries such as South Africa, Singapore, Korea, Ireland and Switzerland are large, which is above 10. Those countries have an obvious advantage in the science and technology development index score than the social innovation development index score. Countries above the line have a higher rank in the social innovation development index score than the science and technology development index score, including 22 countries such as Argentina, Spain, Australia, Belgium, France, the United Kingdom, Norway and Japan. Countries close to the line are basically balanced countries in terms of two sub-indexes, such as Poland, Mexico and Sweden. Countries far away from the line are imbalanced in terms of two sub-indexes, such as Greece, New Zealand and Argentina.

Besides, we find that GDP per capita is closely related to the distribution of 40 countries in the two-dimensional graph. We find most countries with a high GDP per capita are in the top-right corner, while most countries with a low GDP per capita are in the bottom-left corner. Countries in the top-right corner are those with good performance in both science and technology development and social innovation development, most of which are developed countries, such as the Netherlands, Sweden, and Denmark. This finding implies that the level of both the social innovation development index and the science and technology development index to a large extent influences positively the level of economic development.

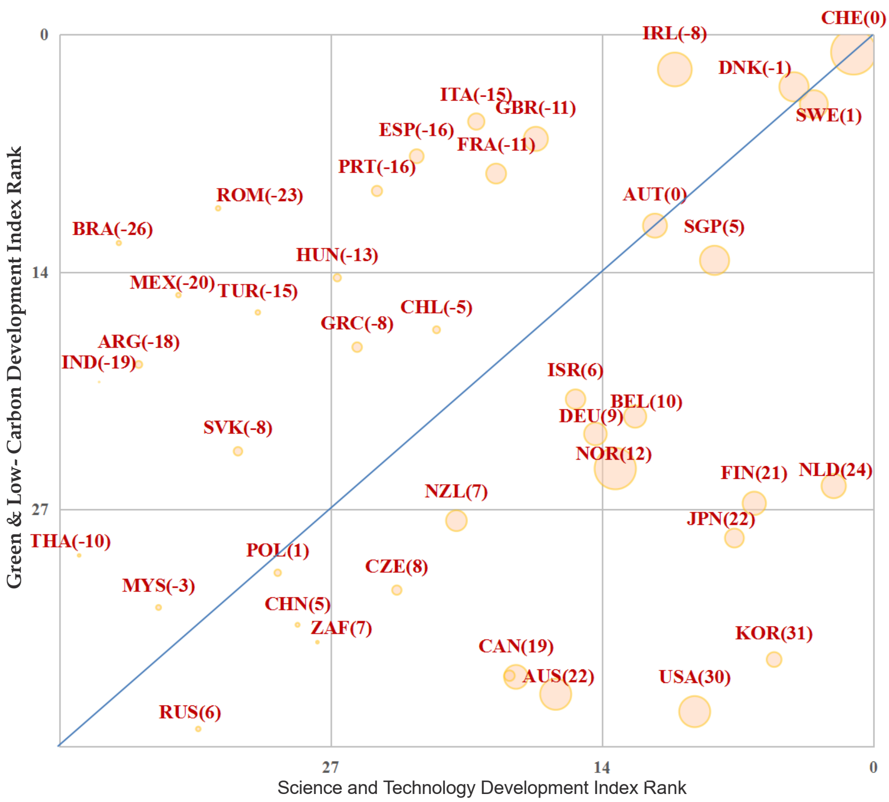

Fig. 10 Cross-analysis between science and technology development index rank and green & low- carbon development index rank (2015)

Note: The bubble area represents the standardized GDP per capita (2015 current price)

This paper draws a two-dimensional graph based on the science and technology development index rank (on the horizontal axis) and the green & low-carbon development index rank (on the vertical axis) (see Fig. 10). The number in parentheses in the figure is the rank difference between the green & low-carbon development index score and the science and technology development index score. The nine-quadrant graph helps to visually present the categories of the 40 countries with the combined consideration of the science and technology development index score and the green & low-carbon development index score.

The diagonal line is a balanced line of the position of 40 countries in terms of the two sub-indexes, different from Fig. 8 and Fig. 9, most countries do not lie around this line, but distribute discretely in Fig. 10. This means that there is no causal relationship between the science and technology development index score and the green & low-carbon development index score. Countries on the line have same ranks in the science and technology development index score and the green & low-carbon development index score, including Austria and Switzerland. Countries below the line have a higher rank in the science and technology development index score than the green & low-carbon development index score, including 19 countries such as China, Japan, Israel, South Africa and Germany. The rank difference of some countries such as Japan, the Netherlands, the United States and Korea is large, which is above 10. Those countries have an obvious advantage in the science and technology development index score than the green & low-carbon development index score. Countries above the line have a higher rank in the green & low-carbon development index score than the science and technology development index score, including 19 countries such as Brazil, Romania, Mexico, India and France. Countries close to the line are basically balanced countries in terms of two sub-indexes, such as Chile, Malaysia and Denmark. Countries far away from the line are imbalanced in terms of two sub-indexes, such as the United States, Korea, Brazil, Romania and Mexico. Clearly, different with Fig. 8 and Fig. 9, the number of countries close to the line is smaller while the number of countries far away from the line larger in the Fig. 10.

Besides, we find that GDP per capita is not related to the distribution of 40 countries in the two-dimensional graph in the Fig. 10. We find most countries with a high GDP per capita are in the right of the graph, while most countries with a low GDP per capita are in the left of the graph. Countries in the right of the graph are those with good performance in science and technology development, most of which are developed countries, such as Switzerland, Sweden, and Denmark. This finding implies that the level of the science and technology development index to a large extent influences positively the level of economic development, while the level of the green & low-carbon development index is not causally related to the level of economic development.

This finding reminds us to pay more attention to the active effect of science and technology development on environmental development in the policy-making process, which confirms the fact that the responsible research and innovation and the transformation innovation receive more and more attention in the literature in recent years.

5. Conclusion and Implications

By studying the connotation of innovation development, this study proposes the national innovation development index (NIDI) to monitor and evaluate the innovation development in a country. Compared with innovative capability, the analytical framework of the NIDI considers not only science, technology and economy development but also social and environment development. Following Mu and Fan's definition of innovation value (Mu and Fan, 2011), the NIDI has been divided into five sub-indexes including science and technology development sub-index, innovation condition development sub-index, industrial innovation development sub-index, social innovation development sub-index and green & low-carbon development sub-index. The five-dimension analytical framework is applied to measure and compare the innovation development performance of selected 40 countries based on a panel of data from 2006 to 2015. The study shows that countries with higher GDP per capita are more likely to have better innovation development performance. We also implement a cross-analysis between science and technology development index and industrial innovation development index. By those systematic analyses, this study can provide evidence for policy-makers to make and improve the innovation development policy of a country.

5.1. Theoretical contributions

Firstly, this study proposes the analytical framework of national innovation development index (NIDI) by extending the connotation of innovation development with the new consideration of the increasingly more important impact of innovation on environment development. A decade ago, Mu et al. (2010) developed an indicator system with five sub-indexes, including: industrialization development, informatization development, urbanization development, education and health development, and science and technology development, to measure the performance of national innovation development from perspectives of science and technology, social and economic development. However, the impact of innovation on environmental development is not clearly recognized and described in the indicator system for innovation development. Therefore, this study provides a systematic understanding of innovation development, and shows the new evolution direction and boundary of innovation development.

Secondly, this study promotes the interdisciplinary studies between innovation studies and development policy studies by integrating the definition of the innovation from five perspectives such as the creation of scientific value, technological value, economic value, social value and cultural value, and the definition of development from four perspectives such as the social development, the economic development, the environment development and the science and technology development. Therefore, this study provides a rational analysis framework for policymakers to improve their understanding on innovation development and utilize the new connotation in the policymaking process related to innovation development so as to reflect the impacts of innovation on environmental development by using indicators such as the social innovation development index and the green & low-carbon development index. Moreover, the analytical framework of NIDI in this study can be used for measuring regional innovation development with some necessary change according to the regional characteristics.

5.2. Practical contributions

This study reveals the trends and shortcomings of some countries in innovation development from its comprehensive level by the NIDI and the performance of different aspects by five sub-indexes. We find that the NIDI scores of all observed countries increased from 2006 to 2015. Furthermore, it is found that most developed countries, especially small-size countries, perform better in the NIDI and its sub-indexes, while some developing countries, especial BRICS countries, display poor performance in both the NIDI and its sub-indexes. All these findings imply that the NIDI score reflects the performance of national innovation-driven development. The comparative analysis implies that the level of national innovation development to a large extent determines the level of economic development. This study tries to build a bridge between innovation measurement and policy-making. It is necessary for governments to choose more specific policies (including science and technology development policies, industry development policies, condition development policies, social development policies and environmental development policies) to overcome shortcomings related to the poor performance of sub-indexes of the NIDI so as to improve their innovation development performance systematically. For example, it is better for Ireland to pay special attention to the performance of social innovation development index while for the United States and Japan to pay special attention to the performance of green & low-carbon development index, and for BRICS countries to pay attention to the performance of science and technology development index for improving their innovation development performance.

5.3. Limitations

This study is to design a perfect and comprehensive analytical framework to measure and compare the innovation development performance of a country based on detailed discussions and extended understanding of the connotation of innovation development in the current and future period. However, the designed framework has to meet some limitations due to date availability. For example, the sub-index of innovation condition development should consist of not only the hard infrastructures for innovation such as digital infrastructures and major large S&T infrastructures, but also the soft infrastructures such as the innovation-friendly institutional support. However, it is difficult to get right statistical data to reflect the soft condition for innovation. Therefore, the proposed NIDI in this paper has no indicator to reflect the impact of innovation institutional environment in a country because of limitation of the statistical data availability in this study. In the follow-up research, we suggest to undertake a systematic survey for comprehensively measuring innovation condition development in a country.

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