Article:

Bi, K., Huang, P. orcid.org/0000-0002-7573-715X and Wang, X. (2016) Innovation performance and influencing factors of low-carbon technological innovation under the global value chain: A case of Chinese manufacturing industry. Technological Forecasting and Social Change, 111. pp. 275-284. ISSN 0040-1625

https://doi.org/10.1016/j.techfore.2016.07.024

Innovation performance and influencing factors of low-carbon technological innovation under the global value chain: A case of Chinese manufacturing industry

Bi Kexin[a, b], Huang Ping[a,*], Wang Xiangxiang[b]
[a] Harbin Engineering University, School of Economics and Management, Harbin 150001, China
[b] Harbin University of Science and Technology, School of Management, Harbin 150080, China [1]

Abstract:
Combing the global value chain framework and linear innovation process model, this paper analyzes the innovation performance of low-carbon technological innovation activities under the global value chain and the influencing factors. Other than previous research on sustainable technological innovation with major focus on radical innovation and socio-technical system transitions activities, this paper places focus on the general innovation characteristics of low-carbon technologies through an integrating view of global value chain and linear innovation process. This paper proposes an analytical framework of the linear innovation process under the global value chain, and uses factor analysis and a DEA-Tobit two-stage method to analyze the low-carbon technological innovation performance and its influencing factors of China's manufacturing industry under global value chain. The results show that the low-carbon technological innovation performance is diverse across different manufacturing industries in China. Moreover, among the three major influencing factors, government regulation is the only factor that shows a positive influence on low-carbon technological innovation performance, yet the effect is quite weak. Technology push displays a negative effect, and the impact of market pull on low-carbon technological innovation performance is not significant.

Key words:
Low-carbon technological innovation; Innovation performance; Influencing factor; Manufacturing industry; Global value chain

1. Introduction

The term of Low-carbon Technological Innovation has been increasingly used in recent innovation researches concerning environmental-friendly technologies, such as researches on low-carbon technologies of manufacturing industries (Bi et al., 2015) and marine renewable energy technologies (MacGillivray et al., 2014), which shares a great amount of similarities with the concept of eco-innovation (Rennings, 2000) and technological change (Löschel, 2002). Considering that the carbon-based socio-technical system is possibly the biggest socio-technical system in the history, technological innovation aiming for carbon reduction might lead to a complete transformation of the carbon-based socio-technical system (Jacobsson and Bergek, 2004), which requires system innovation and transitions. Following the major viewpoint, innovation scholars placed great attentions to innovation activities such as radical innovation of low-carbon technology (Bergek et al., 2008; Hekkert et al., 2007) and socio-technical system innovation and transitions (Geels, 2002; Geels and Schot, 2007; Smith et al., 2010). However, incremental innovation activities of carbon reduction technologies have been largely neglected in the mainstream of low-carbon innovation scholarship.

To uncover the general innovation characteristics of low-carbon technologies, turning back to the essence of innovation elaborated in Schumpeter's Innovation Theory, in this paper we view low-carbon technological innovation as innovation activities that not only increases in outputs without increases in productive inputs, but also enhances energy-efficiency and lowers carbon emission intensity through "product innovations, i.e., higher energy-efficiency of existing and new products, and process innovations, i.e., higher energy-efficiency of manufacturing processes, cost reductions in low-emission energy conversion and improvements in fossil energy conversion" (Löschel, 2002: p.105).

Following Schumpeter's conceptualization of innovation, innovation is generally viewed as a three-stage process, consisting of invention, innovation, and diffusion (Schumpeter, 1934). Based on the linear innovation model, Stern (2007) proposed a new innovation model for climate change related technologies that included policy intervention and investment activity, which aimed to investigate the general characteristics and

[1] * Corresponding author at: School of Economics and Management, Harbin Engineering University, China.
E-mail address: huang_ping1987@hotmail.com.
Present address: No. 145-1, Nantong Street, Nangang District, 150001 Harbin, Heilongjiang Province, China.

innovation process of climate adaptation technologies. Thus, in this paper we use the expanded linear innovation model as an instrument to investigate the innovation performance and influencing factors of low-carbon technological innovation.

Ever since the announcement of UK Energy White Paper 'Our energy future - creating a low carbon economy' in 2003, the majority of low-carbon technological innovation research focused on emerging technologies and industries, such as wind power (Gosens and Lu, 2013), solar photovoltaic (PV) (Klitkou and Coenen, 2013), biomass (Breukers et al., 2014), carbon capture and storage (CCS) (Van Alphen et al., 2010) etc. Meanwhile, innovation activities that seek to improve energy efficiency and reduce carbon emission in traditional manufacturing industries also saw an explicit growth. However, just a few innovation scholars had focused on low-carbon innovation in manufacturing industries (Bi et al., 2015; Uyarra et al., 2016). In fact, manufacturing industry accounts for a large amount of carbon emission, especially for newly industrializing economies.

Taking China for example, manufacturing industry accounted for 47% of the total carbon emission in 2012 (Liu, 2015). In the meantime, a strategic plan called 'Made in China 2025' that released by the Central Government of China in 2015 has proposed an ambitious carbon reduction target for China's manufacturing industry: compared to 2015, energy consumption and CO_2 emission per unit of added value for large-scale industrial enterprises dropped by a total of 18% and 22% respectively. On the other hand, China's manufacturing industry also acts as the main pillar of economic growth and employment opportunities. It is fair to say that manufacturing industry in China is facing dual pressures of carbon emission reduction and sustainable economic development. This leads to the question that how China's manufacturing industry could achieve low-carbon transition and sustainable development at the same time?

Since China became a member of World Trade Organization (WTO) in 2001, China's manufacturing industry began to get involved in the global value chain. And just in a short period of time, China became the 'world factory' with huge trade surplus. The term Global Value Chain (GVC) was first proposed by Gereffi and Korzeniewicz (1994), and thereafter has been widely used by major scholars in this field. The United Nations Industrial Development Organization (UNIDO) defined GVC as a global cross-enterprise network that realizes the value of goods or services, which links production, sales, recycling and other processes (UNIDO, 2003).

Accompanying with increasing economic globalization and international labor division, GVC governance begins to play a more and more important role in manufacturing development and upgrading (Gereffi et al, 2005; Humphrey and Schmitz, 2002), especially for emerging and developing economics such as China that are still at the stage of low added-value production or assembly activities. The 'low-end locking' issue for China's manufacturing industry is believed to be the consequence of monopoly of a few global enterprises on high added-value activities such as R&D of key technologies, and brand marketing (Morrison, 2008). In the meantime, emerging low-carbon economy at global scale is urging for a low-carbon transformation of traditional manufacturing industries with high energy consumption and pollution emission. This represents both opportunity and challenge for China's manufacturing industry to break the 'low-end locking', and to achieve low-carbon upgrading in the GVC. In this context, stimulating low-carbon technological innovation activities in China's manufacturing industry is viewed as a fundamental solution (Chiarolla, 2008). The key role of low-carbon technological innovation has also been tested in case studies of both developed and developing countries (Henriques et al., 2010; Park et al., 2009).

Thus, in this paper we analyzed the innovation performance and influencing factors of low-carbon technological innovation of China's manufacturing industry under the GVC, and provided a few policy implications for Chinese government to stimulate low-carbon upgrading of China's manufacturing industry. The structure of the paper is as follows: firstly, we integrated the linear innovation model and GVC framework together as the analytical framework to investigate innovation performance and influencing factors of low-carbon technological innovation activities in manufacturing industry. Secondly, using factor analysis and a DEA-Tobit two-stage method, the low-carbon technological innovation performance and its influencing factors were evaluated and analyzed. At last, we proposed several policy implications based on empirical analysis results.

2. Theoretical framework

The GVC framework has been widely used to investigate the dynamics of technology development under the globalization (Bi, et al., 2015; Kiamehr, 2016; Pietrobelli and Puppato, 2015). For our case study of Chinese manufacturing industry, every component of Chinese manufacturing industries is highly embedded in the GVC, especially with regard to low-carbon R&D, manufacturing, and marketing activities. When it comes to low-carbon technologies, transnational technology transfer and secondary innovation play a much more important role in China (Zhang and Gallagher, 2016). Moreover, GVC as a framework can bring domestic innovation activities and global governance together, which emphasizes the interaction between domestic manufacturers and the global production network (Pietrobelli and Rabellotti, 2011). The GVC framework is able to lead us to a better understanding of the exchange of technical knowledge, market information, and feedback in the innovation process. Thus, combing the GVC framework into innovation process analysis is necessary for us to observe each stage of innovation processes under the governance of the GVC. This is especially essential for an emerging economy like China, which to some extent can avoid the misleading to overestimation of Chinese innovation capacity that tends to overlook the major role of foreign technology import.

2.1. The value creation process under the GVC

As a chain that links production, sales, recycling and other processes, GVC involves various value creation activities including design, product development, manufacturing, marketing, after-sales service and recycling (UNIDO, 2003). KaPlinsky and Morris (2001) singled out four elements of a value chain, constituting design and product development, production, marketing, as well as consumption and recycling. They also categorized design and product development and marketing as strategic value elements, which are able to create higher added-value in the GVC. On the other hand, manufacturing is viewed as low added-value activities. The difference of value creation capacity of elements along the GVC forms a U-shaped curve, which is vividly named as 'smile curve' (Mudambi, 2007). In this paper, we focus on three major elements of the GVC: research and development (R&D), manufacturing, and marketing.

2.2. The linear process of low-carbon technological innovation under the GVC

The linear innovation model proposed by Kline and Rosenberg (1986) argued that innovation was a linear process involving research, development, manufacturing, and marketing activities. It is generally accepted that R&D, manufacturing, and marketing are the key stages of innovation process. Moreover, a few innovation scholars have placed the linear innovation process under the GVC. Schmitz (2004) argued that manufacturers in the developed countries have always been the main actors of innovation activities under the GVC, even though manufacturers from developing countries begin to gain more market share. For manufacturers in developing countries, getting involved in the GVC does not necessarily translate into higher innovation performance. Even though most of incremental innovation activities can be conducted by "learning by doing", it still requires a certain level of learning capacity (Morrison, 2008; Pietrobelli and Rabellotti, 2011). Nevertheless, learning through importing product or technology is an important pathway to strengthen innovation capacity for manufacturers in developing countries.

In this context, it is necessary to investigate innovation activities of manufacturing industry under the GVC. We propose to integrate the linear innovation model and GVC framework together as the analytical framework in this paper. And the linear innovation process of low-carbon technological innovation under the GVC is investigated as a process constituting three main elements: global low-carbon R&D, global low-carbon manufacturing, and global low-carbon marketing.

2.3. The influencing factors of low-carbon technological innovation performance under the GVC

Market pull and technology push have long been recognized as the key influencing factors of innovation performance of product and process technologies (Palm et al., 2004; Su and Liu, 2012; Woerter, 2009). When it comes to low-carbon innovation, due to the "dual externality" that may both provide R&D spillovers and reduce environmental negative externalities, government regulations become the essential factors as well (Horbach, 2008; Horbach et al., 2012; Rennings, 2000).

The ultimate value of innovation is realized through the market. A few studies indicated that market demand and market competition, regarded as origins of market pull, play significant roles in stimulating technological innovation (Palm, 2004; Woerter, 2009). In regard to technology progress, the history of science and technology development shows that major breakthroughs in science and technology can lead to a wave of innovation activities. It has been investigated that technology progress has a significant positive effect on low-carbon technological innovation performance (Woerter, 2009), which also acts as a key factor to improve energy efficiency that resulting in upgrading in the GVC (Humphrey, 2004). In addition, government regulations are regarded as strong stimuluses for low-carbon innovation (Cole, 2005). This is also highlighted by "Porter hypothesis", which argues that stringent environmental regulation will result in innovative compensation, leading to a higher efficiency of resource utilization and economic performance in the long run (Rennings and Rammer, 2011).

Therefore, in this paper we integrate the linear innovation model and GVC framework together as the analytical framework to investigate low-carbon technological innovation activities through three elements: global low-carbon R&D, global low-carbon manufacturing, and global low-carbon marketing. Based on the framework (Fig. 1), we analyze the influencing factors of government regulation, technology progress, and market pull, and then evaluate the low-carbon technological innovation performance.

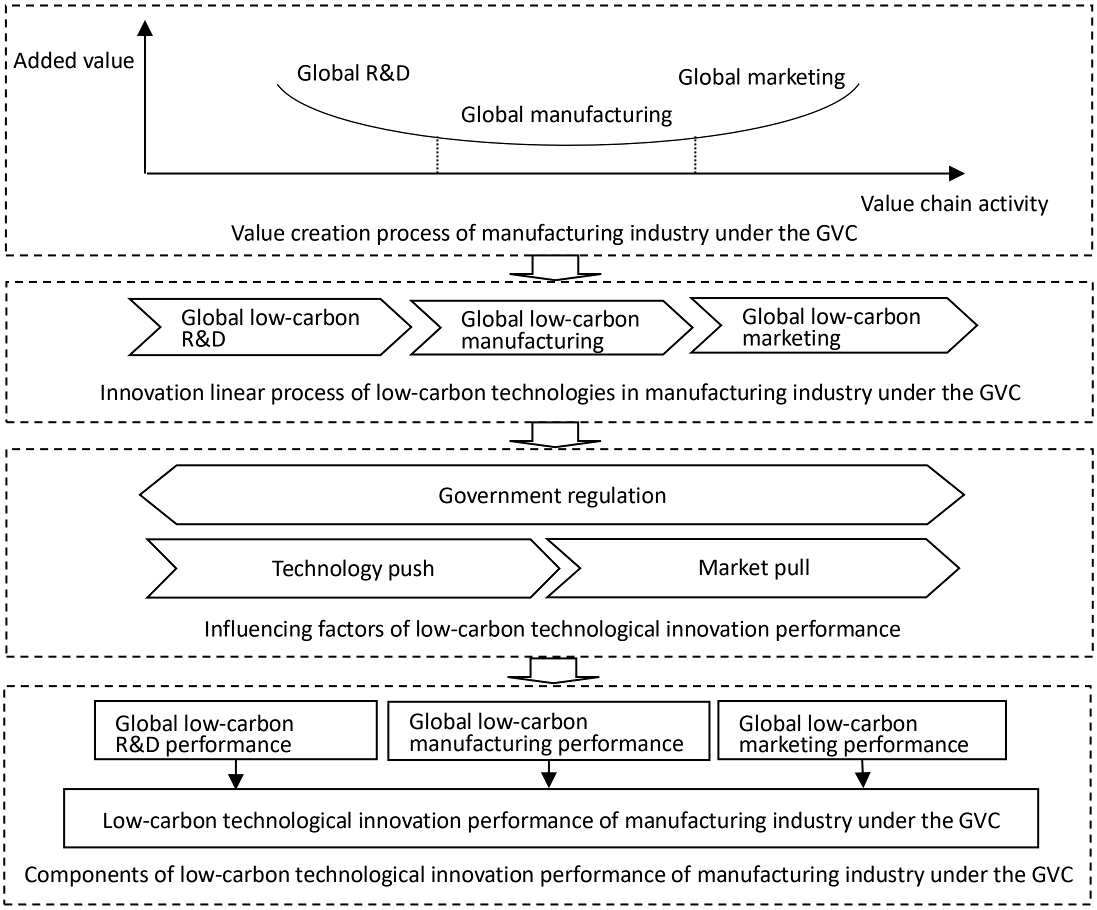

Fig. 1. Analytical framework of the linear innovation process under the GVC

3. Methodology

3.1. Two-stage Method: DEA-Tobit

Data Envelopment Analysis (DEA) method has been widely used to conduct input-output analysis for innovation performance (Chen, et al., 2016; Lee and Yoon, 2015). Because innovation process involves too many factors, it is better to view innovation process as a 'black box' and place the focus on innovation inputs and outputs (Chen and Guan, 2012; Kaihua and Mingting, 2014). Conducting a comprehensive evaluation on the relative efficiency of multi-input and multi-output decision-making unit, DEA does not require a function hypothesis between variables, while the weight of input and output indexes are calculated by the actual value of decision-making unit. Moreover, the DEA based efficiency value calculation is not affected by the difference between units of measurement, and it is not necessary to ensure dimensionless.

Referring to recent methodology development and design of DEA (Cruz-Cázares et al., 2013; Hung and Wang, 2012; Kaihua and Mingting, 2014), we applied a DEA-Tobit two-stage method to evaluate the innovation performance and the impact of selected influencing factors. In regard to a DEA-Tobit two-stage method, the first step is to assess the efficiency value of decision-making unit using DEA method; and the second step is to build a regression model with the efficiency value calculated in the first step as dependent variables and influencing factors as explanatory variables. The efficiency value calculated by DEA method ranges from 0 to 1, thus, the dependent variable of the regression equation is limited to the range (0, 1). Conventional least square method will make the parameter estimation deviated and inconsistent (Greene, 1981), we therefore adopt the Tobit regression model. Tobit regression model is a regression model of which the dependent variable is restricted, and it is suitable for cases in which dependent variable is truncated or censored (Tobin, 1958).

In addition, among the DEA models, C^2R model is not able to separate technical efficiency and scale efficiency (SE), while BC^2 model can divide the efficiency value calculated by C^2R model into total factor efficiency (TFE) and scale efficiency, which will lead to lack of efficiency (Banker, 1984). Considering the data characteristics of low-carbon technological innovation under the GVC, input control is more practical than output control. Therefore, the input-oriented BC^2 model is selected in this paper. Moreover, considering that the credibility of evaluation might be lowered when there is a strong linear correlation among input indicators or output indicators, we conduct a factor analysis before the DEA-Tobit analysis.

Innovation performance analysis of general innovation activities mainly focuses on a few selected input indicators such as R&D employees and R&D expenditure, and output indicators such as number of patents and turnover of new products (Cruz-Cázares et al., 2013; Lee and Yoon, 2015; Kaihua and Mingting, 2014; Moon, 2013). These selected input and output indicators seem adequate for general innovation performance evaluation. However, when it comes to innovation performance of low-carbon technologies, which not only involves technological and financial performance, but also includes environmental and low-carbon performance, it is inadequate to solely use these “popular” input and output indicators.

Responding to the needs of low-carbon innovation analysis, more and more energy and carbon emission related indicators and contextual indicators have been introduced into the analysis of low-carbon innovation performance (Chen, et al., 2016; Valadkhani, et al., 2016; Yang and Yang, 2015). On the one hand, other than involving the common input indicators, such as labour and capital, Valadkhani, et al. (2016) also included a few environmental indicators, like freshwater and energy. Regarding the output indicators, three undesirable outputs have been included: CO_2, methane and nitrous oxide emissions. They found that different ways of utilization of resources like freshwater and energy will increase or decrease the emissions of three separate greenhouse gases (CO_2, methane and nitrous oxide), in which the low-carbon technologies were regarded as the main cause. Thus, energy and carbon emission related elements need to be involved into the output indicators of low-carbon technological innovation performance, for example, the increase or decrease of fossil energy consumption and carbon emission intensity.

On the other hand, Chen, et al. (2016) selected seven indicators as input factors for the measurement of the energy efficiency of China's regional construction industry, in which energy input, labor input, capital input, and construction machinery and equipment input are viewed as direct input variables, while energy consumption structure, industrial development degree, and organization structure and technological level are conceived as indirect contextual variables. It is fair to say that when it comes to energy and environmental efficiency, landscape forcing plays an essential role in the transformation process. Moreover, considering the embeddedness of Chinese manufacturing industries into the GVC, it is necessary to consider more contextual input indicators, especially the ones related to GVC governing in the low-carbon technological innovation analysis, such as the foreign direct investment volume, the production scale, the utilization level of existing international marketing channels, and the globalization degree.

In this paper, taking the energy and carbon emission related indicators and contextual indicators into consideration, as well as the role of GVC governing, we develop the following index system for the analysis of low-carbon technological innovation performance.

3.2. Index system

3.2.1. Input index of low-carbon technological innovation

(1) The personnel input intensity of low-carbon technology in global manufacturing innovation. It mainly refers to low-carbon technology R&D personnel input in the process of global manufacturing industry innovation and reflects the personnel support to low-carbon technological innovation activities, expressed by the ratio of personnel input of low-carbon technology in global manufacturing industry innovation to employees of manufacturing industries (Feng, 2010).

(2) The funding intensity of low-carbon technology in global manufacturing innovation. It mainly refers to low-carbon technology R&D funding in the process of global manufacturing industry innovation and reflects the financial support to low-carbon technological innovation activities, expressed by the ratio of funding for low-carbon technology in global manufacturing industry innovation to the main business income of manufacturing industries (Feng, 2010 NBS, 2010).

(3) The foreign direct investment volume in manufacturing industry's low-carbon technological innovation. It reflects the degree of international resources utilization in manufacturing industry's low-carbon technological innovation, expressed by the amount of foreign direct investment in manufacturing industry's low-carbon technological innovation.

(4) The production scale of manufacturing industry's global low-carbon products (technology, service). Production scale refers to the concentration degree of means of production, labor, and product in the enterprise. The index to measure the scale of production is mainly production capacity and output, wherein production capacity refers to the maximum output of the enterprise and the output is the actual output of the enterprise (Hu and Gu, 2006). This paper uses industry output value to represent it, as the output value is the total value of industrial finished products or industrial service supplies of the enterprise in a certain period that reflects the total production outcome, and indicates the enterprise's overall scale of industrial production.

(5) The utilization level of existing international marketing channels for manufacturing industry's global low-carbon products (technology, service). Marketing channel is an enterprise's nerve endings in the market, which directly interacts with the market demand and changes. International competition refers to not only competition of product and brand, but also the competition of distribution efficiency (Du, 2008). The depth and breadth of manufacturing industry's utilization of international marketing channels determine the low-carbon product (technology, service) coverage. When selecting and utilizing international marketing channels, influencing factors like costs, market coverage, capital and control should be taken into consideration. The operating expense refers to expenses that occur during product marketing and sale, and other related everyday service, as well as expenses that used to set up specialized sales organization, including expenses like advertising expense, exhibition expense, lease expense, etc. The growth rate of the proportion of manufacturing industry's operating expense to manufacturing industry's sales value can well reflect the level of marketing channel utilization. Therefore, this paper uses the growth rate of the proportion of manufacturing industry's operating expense to manufacturing industry's sales value multiplied by the proportion of low-carbon technology in manufacturing industry under GVC to approximate the utilization level of existing international marketing channels for manufacturing industry's global low-carbon products (technology, service).

(6) The globalization degree of manufacturing industry's low-carbon supply chain. Supply chain refers to the chain structure, channel or network, consisting of raw material suppliers, manufacturers, distributors, retailers and consumers. It regards the process from raw materials and components purchase, transportation, manufacturing, and distribution to the final delivery to consumers as an interlocking chain (Lan, 2003). When extending the supply chain system to the entire world, we can fully and quickly know the demand preference of consumers around the world, adapt to the requirements of the global market to achieve immediate sale, production and supply in every link of the supply chain, and create conditions for a greater share in the international market. The sales rate of industrial products sales reflects the degree of sales realization, and finished products sales reflect the degree of supply chain to some extent. Therefore, this paper uses manufacturing industry's finished products sales multiplied by the proportion of low-carbon technology in manufacturing industry under GVC to approximate the globalization degree of manufacturing industry's low-carbon supply chain.

3.2.2. Output index of low-carbon technological innovation

(1) The number of internationally authorized invention patents about manufacturing industry's low-carbon technology. Among the three patents of invention, utility model and design, invention patent can best reflect the level of technological innovation (Yang, 2011). Low-carbon technology patent is the output of the previous innovation activities and the input of the follow-up innovation activities. It is the direct reflection of innovation. The number of overseas authorized patent among the effective invention patents, referring to the number of patents owned by the patentees in the end of report period, authorized by the intellectual property administrative authorities of foreign countries, Hong Kong, Macao or Taiwan, and within the validity period, can measure the number of internationally authorized invention patents in manufacturing industries. It is a

positive indicator.

(2) The manufacturing industry's fossil energy consumption per unit of output under the GVC. It equals the ratio of the manufacturing industry's fossil energy consumption to the manufacturing industry's output value. Industrial activities have a great demand for fossil fuels, and fossil energy is currently the world's main consumption energy. The use of fossil fuels will produce a great deal of carbon emissions, and thus impact the global climate. Generally it includes coal consumption, coke consumption, oil consumption, gasoline consumption, kerosene consumption, diesel consumption, fuel consumption and natural gas consumption. It is a negative indicator (Li, 2013).

(3) The carbon emission intensity of the international trade of manufacturing industry. It equals the ratio of the carbon emission degree of the international trade of various industries in manufacturing to the industry output value, reflecting the relationship between economic development of manufacturing industry and carbon emission. If the amount of carbon emission brought by every unit of GNP is decreasing while the economy is growing, then it indicates that the manufacturing industry has achieved a low-carbon development model. It is universally recognized by the international community as the indicator that can best embody the development of low-carbon. It is a negative indicator (Li, 2013).

(4) The manufacturing industry's CCS degree under international cooperation. In Cancun conference, the CCS technology was incorporated into the Clean Development Mechanism (CDM) project. CCS technology can reduce carbon emission on a large scale. Due to its flexibility and wide coverage, CCS has received more attention (Tavoni, 2012), and is recognized as one of the most important key technologies to mitigate global climate change. In fact, the carbon capture and storage degree of each manufacturing industry is not balanced. However, due to difficulty in data extraction, it is assumed to be balanced in this paper. And this paper uses the proportion of carbon capture and storage amount to carbon emission amount multiplied by the carbon emission amount of manufacturing industries to approximate the manufacturing industry's carbon capture and storage amount. It is a positive indicator.

(5) The proportion of manufacturing industry's low-carbon technology output value under international cooperation to total output value. It reflects the manufacturing capacity of low-carbon technological innovation in manufacturing industry. It is a positive indicator.

(6) The growth rate of manufacturing industry's low-carbon transformation rate under international cooperation. Due to the lack of relevant data of low-carbon transformation rate, it is usually approximated by the ratio of the number of international invention patent applications about low-carbon technology of each manufacturing industry to the total number of patents. The reason is that low-carbon technological innovation is manufacturing enterprises' main means for low-carbon transformation. The growth rate of low-carbon transformation rate is a positive indicator.

(7) The international market share of manufacturing industry's global low-carbon products (technology, service). International market share index is the proportion of a country's total export volume to the world's total export volume that reflects the country's overall export competitiveness (Zhang, 2001). The international market share of low-carbon products (technology, service), i.e., the proportion of low-carbon products export volume to the world's total export volume, is a positive indicator. Low-carbon technological innovation emphasizes low-carbon products (technology, service) R&D and manufacturing, and ultimately gains benefit through commercialization. The key criteria to decide whether the low-carbon technological innovation of manufacturing industry under GVC is successful or not is the realization degree of low-carbon products (technology, service) market, i.e., the international market share and exportation foreign exchange gained by manufacturing industry by the means of low-carbon technological innovation.

(8) The total foreign exchange earnings of manufacturing industry's global low-carbon products (technology, service). It is closely related to innovation (LööF, 2001). Since the data about low-carbon product (technology, service) export is not available, this paper uses the export delivery value of manufacturing industries' products as measurement indicator. It is a positive indicator. Export delivery value refers to the product value settled in foreign exchange, as well as product value produced by foreign samples, parts assembly, trade compensation, etc. The products are hand over from industrial enterprises to foreign trade departments for export or self-support (commissioned) export.

Based on the above analysis, the assessment indicator system for low-carbon technological innovation performance of manufacturing industry under GVC is shown in Table 1.

Table 1
Evaluation system of manufacturing low-carbon technological innovation performance in the global value chain

Dimensions	Index layer
Input	I1: personnel input intensity of low-carbon technology in global manufacturing innovation I2: funding intensity of low-carbon technology in global manufacturing innovation I3: foreign direct investment volume in manufacturing industry's low-carbon technological innovation I4: production scale of manufacturing industry's global low-carbon products (technology, service) I5: utilization level of existing international marketing channels for manufacturing global low-carbon products (technology, service) I6: globalization degree of manufacturing industry's low-carbon supply chain
Output	O1: number of internationally authorized invention patents about manufacturing low-carbon technology O2: manufacturing industry's fossil energy consumption per unit of output under the GVC O3: carbon emission intensity of the international trade of manufacturing industry O4: manufacturing industry's CCS degree under international cooperation O5: proportion of manufacturing industry's low-carbon technology output value under international cooperation to total output value O6: growth rate of manufacturing industry's low-carbon transformation rate under international cooperation O7: international market share of manufacturing industry's global low-carbon products (technology, service) O8: total foreign exchange earnings of manufacturing industry's global low-carbon products (technology, service)

3.3. Data source

In this paper we study the low-carbon technological innovation performance of China's manufacturing industry under GVC by extracting all of the industries in manufacturing industry as research objects. It is worth noting that the classification of industries used in this paper is still in accordance with 'National Industries Classification' (GB/T4754-2002), since the new industry standard 'National Industries Classification' (GB/T4754-2011) was implemented in 2012 and the data used is before December 31, 2011. Data of 'waste resources and materials recycling and processing industry' is not included due to inconsistence. Hence, a total of 29 manufacturing industries decision units are adopted as research objects. For simplicity and accuracy, we encode these 29 industries as shown in Appendix A.

The commercialization of innovation from input to new patents, new products (technology, service) usually requires a certain period. Specifically speaking, the process from input to output has a lag period, so there is a huge difference between the cycles of different innovation activities. Some scholars suggested that the delay from input to output of innovation is 1 year (Kirchhoff, 2002), or 2 years (Bai, 2009). Considering that the emergence of economic effect, environmental effect, and social effect of low-carbon innovation activities takes more time than general innovation activities, the lag period in this paper is set to 2 years. This paper chooses data of 2007-2009 as the input of low-carbon technological innovation and the corresponding data of 2009-2011 as output. The main source of data in this paper is statistical yearbooks from 2008 to 2012, including 'China Statistical Yearbook', 'Statistics on Scientific and Technological Activities of Industrial Enterprises', 'China Industrial Economy Statistical Yearbook', 'China Energy Statistical Yearbook', 'China Foreign Economic Trade Statistical Yearbook', 'China Science and Technology Statistical Yearbook', etc. Other source of data includes reports like 'Research Report on China's Manufacturing Industry Development (2012)', 'Research Report on Global CCS Development' and materials like 'Statistical Bulletin of China's OFDI (2012)', the patent retrieval and service system of State Intellectual Property Office, WTO statistics database, 'CO_2 Emissions from Fuel Combustion Highlights (2013)'. The raw data of input and output indicators as well as influencing factors is shown in Appendix B.

4. Performance evaluation and influencing factors analysis

4.1. Factor analysis

Based on the established low-carbon technological innovation performance indicator system, we first normalize all the original data in SPSS 21.0 software, and then conduct the factor analysis. Manufacturing fossil energy consumption per unit of output in the GVC, and manufacturing carbon intensity in international trade are negative indicators. Therefore, this paper uses linear conversion method to ensure the positive terms unity of output. Specific formula is:

$$Y'_{ij} = -Y_{ij} + \max_{1 \le j \le m} Y_j \quad (1)$$

Firstly, this paper tests KMO values, Bartlett's sphericity test and an explanation of the total variance are shown in Table 2.

Table 2
The KMO and Bartlett's test

		2007 input	2009 output	2008 input	2010 output	2009 input	2011 output
KMO measure of sampling sufficient		0.660	0.587	0.583	0.536	0.753	0.638
Bartlett's test of sphericity	Approximate chi-square	456.075	536.948	453.024	536.948	520.734	583.34
	df	15	28	15	28	15	28
	Sig	0.000	0.000	0.000	0.000	0.000	0.000

KMO values are bigger than 0.5 and the probability of Bartlett's sphericity test is 0.000, less than the significance level of 0.01, which means that there is a correlation among the original indexes, and thus is suitable for factor analysis. The standard for choosing factors is whether the eigenvalues are greater than 1. Principal component method is used to extract common factors of inputs and output indicators. The cumulative variance contribution rate of input indicators reach 98.868%, 98.330%, 94.071% respectively, meaning that the two input public factors extracted can illustrate all the variables. Using the same method, two output common factors are extracted, and the cumulative variance contribution rate reach 85.824%, 83.032%, 80.558%, covering almost all of the information.

4.2. Performance evaluation

Based on data processing and calculation using the input-oriented BC2 model of DEA method (see Appendix C), this paper uses DEAP 2.1 software to calculate the efficiency value. After that we analyze the low-carbon technological innovation performance of Chinese manufacturing in the GVC. The results are shown in Table 3.

Table 3
The evaluation results of Chinese manufacturing low-carbon technological innovation performance in the GVC

DMU	2007-2009				2008-2010				2009-2011			
	TE	PTE	SE	RS	TE	PTE	SE	RS	TE	PTE	SE	RS
1	0.665	0.990	0.672	irs	0.905	0.995	0.910	irs	0.815	0.998	0.816	irs
2	1.000	1.000	1.000	-	0.750	0.982	0.764	irs	0.570	0.992	0.574	irs
3	0.583	1.000	0.583	irs	1.000	1.000	1.000	-	0.589	0.982	0.600	irs
4	0.780	1.000	0.780	irs	0.919	1.000	0.919	irs	0.793	0.998	0.794	irs
5	0.712	0.997	0.714	irs	0.818	1.000	0.818	irs	0.836	1.000	0.836	irs
6	0.679	1.000	0.679	irs	0.733	0.987	0.743	irs	0.799	0.999	0.800	irs
7	0.722	1.000	0.722	irs	0.797	1.000	0.798	irs	0.802	0.999	0.802	irs
8	0.589	1.000	0.589	irs	0.744	0.981	0.759	irs	0.703	0.997	0.705	irs
9	0.741	0.991	0.748	irs	0.767	1.000	0.767	irs	0.674	0.995	0.677	irs
10	0.509	1.000	0.509	irs	0.758	0.950	0.798	irs	0.743	0.998	0.745	irs
11	0.748	1.000	0.748	irs	0.738	0.986	0.748	irs	0.694	1.000	0.694	irs
12	0.674	0.985	0.685	irs	0.721	0.973	0.742	irs	0.710	0.999	0.710	irs
13	1.000	1.000	1.000	-	0.753	1.000	0.753	drs	0.677	1.000	0.677	drs
14	0.735	0.741	0.992	drs	0.864	0.998	0.865	drs	1.000	1.000	1.000	-
15	0.750	0.980	0.766	irs	0.746	0.978	0.762	irs	0.546	1.000	0.546	irs
16	0.609	0.995	0.612	irs	0.749	0.998	0.750	irs	0.748	0.999	0.748	irs
17	0.548	0.944	0.581	irs	0.768	1.000	0.768	irs	0.590	1.000	0.590	irs
18	0.569	0.958	0.594	irs	0.742	0.964	0.770	irs	0.642	0.997	0.643	irs
19	1.000	1.000	1.000	-	0.893	1.000	0.893	irs	0.997	1.000	0.997	irs
20	1.000	1.000	1.000	-	1.000	1.000	1.000	-	1.000	1.000	1.000	-
21	0.695	1.000	0.695	irs	0.817	0.961	0.850	irs	0.643	0.950	0.677	irs
22	0.777	1.000	0.777	irs	0.806	0.982	0.820	irs	0.669	0.993	0.674	irs
23	0.885	0.955	0.926	drs	0.719	0.813	0.884	drs	1.000	1.000	1.000	-
24	0.830	1.000	0.830	irs	0.890	0.996	0.893	irs	0.766	1.000	0.766	irs
25	0.675	0.840	0.803	irs	0.769	0.792	0.971	irs	0.837	0.935	0.895	irs
26	1.000	1.000	1.000	-	0.947	1.000	0.947	drs	1.000	1.000	1.000	-

27	1.000	1.000	1.000	-	1.000	1.000	1.000	-	1.000	1.000	1.000	-
28	1.000	1.000	1.000	-	1.000	1.000	1.000	-	0.941	1.000	0.941	irs
29	0.824	0.998	0.827	irs	0.810	1.000	0.810	irs	0.791	0.999	0.791	irs

Note: TE refers to overall technical efficiency, PTE refers to pure technical efficiency, and SE refers to scale efficiency, wherein TE=PTE×SE; in addition, RS refers to the condition of Return of Scale, drs refers to decreasing Return of Scale, irs refers to increasing Return of Scale, and - refers to constant Return of Scale.

4.3. Influencing factor analysis

In this paper, the dependent variable is the overall technical efficiency of low-carbon technological innovation in manufacturing industry, and the explanatory variables are market pull (*MP*), technology push (*TP*) and government regulation (*GR*). The Tobit model is shown as following.

$$\begin{aligned} TE_{it}^{*} &= C + \beta_1 MP_{it} + \beta_2 TP_{it} + \beta_3 GR_{it} + \varepsilon_{it} \\ TE_{it} &= TE_{it}^{*} \ \text{if} \ TE_{it}^{*} > 0 \\ TE_{it}^{*} &= 0 \ \text{if} \ TE_{it}^{*} \le 0 \end{aligned} \tag{2}$$

In the equation, TE_{it} is the overall technical efficiency; MP_{it} is market pull; TP_{it} is technology push; and GR_{it} is government regulation. Considering the data availability, in this paper we respectively use new product sales revenue of the manufacturing industry multiplied by the proportion of low-carbon technology in the manufacturing industry under the GVC, the contribution rate of technology push multiplied by the decrease rate of manufacturing industry’s fossil energy consumption per unit of output, and the proportion of government funding to manufacturing industries’ R&D expenditure multiplied by the decrease rate of manufacturing industries’ carbon emission increment under the GVC to measure the impact of market pull, technology push, and government regulation on low-carbon technological innovation performance.

In regard to the evaluation of the impact of market pull, among the available databases, the new product sales revenue can better reflect the product cycle, market competitiveness, and economic benefits, which makes it a good indicator for technological innovation achievements (Gao and Wan, 2011). And the low-carbon product sales can be measured through the proportion of low-carbon technology patents. Then we can use the ratio of the sum of manufacturing industry’s foreign capital, capital from Hong Kong, Macao and Taiwan, and outward foreign direct investments to the sum of foreign capital, capital from Hong Kong, Macao and Taiwan and domestic capital to approximate the degree of manufacturing industry’s participation in globalization.

Regarding the evaluation of the impact of technology push, the contribution rate of technology push is an important aggregative indicator to reflect the role of science and technology advancement and the effect of the change of economic growth mode (Feng and Li, 1996). And the indicator of manufacturing industries’ fossil energy consumption per unit of output can reflect the industry's dependence on fossil fuels (Wang, 2003), thus, the decrease in manufacturing industry’s fossil energy consumption per unit of output will represent the degree of saving energy after technology push.

As to the evaluation of the impact of government regulation, the proportion of government funding to the manufacturing industry’s R&D expenditure can reflect government’s guidance and encouragement to the manufacturing industry’s technological innovation. And we use the decrease rate of the manufacturing industry’s carbon emission increment to represent the carbon reduction effect of successful low-carbon technological innovation.

Considering that the performance evaluation has lag phases, this paper uses the averages influencing factors of 2007-2009, 2008-2010 and 2009-2011, and employs software Eviews 5.0 for Tobit regression analysis. The results are shown in Table 4.

Table 4
Analysis of the influencing factors of low-carbon technological innovation performance of China's manufacturing industry under GVC

Variable	Coefficient	Std. Error	z-Statistic	Prob
MP	1.65E-08	1.63E-08	1.008968	0.3130
TP	-0.008008	0.005447	-1.470209	0.1415

GR	0.000162	0.000399	0.405472	0.6851
C	0.772715	0.016922	45.66398	0.0000

Note: R-squared=0.048565；Log likelihood=52.86248

5. Result analyses

5.1. Performance evaluation of low-carbon technological innovation in Chinese manufacturing industry

According to the 2007-2009, 2008-2010, 2009-2011 and overall efficiency value changes, the low-carbon technological innovation performance of China's manufacturing industry under the GVC is divided into four levels in accordance with average overall technical efficiency calculated.

Manufacturing industries with overall technical efficiency equal to 1 are of high performance, including Smelting and Pressing of Ferrous Metals, Manufacture of Communication Equipment, Computers and Other Electronic Equipment. Although Smelting and Pressing of Ferrous Metals is a high-energy-consuming and high-polluting industry, it has a high innovation input and a matched high level of output. Communication equipment, computer and other electronic equipment manufacturing industries are some of China's most open-ended and fastest growing high-tech industries (Wu and Mu, 2005), playing a very important role in the national economy. It can be seen from the low-carbon technological innovation output data that in Manufacture of Communication Equipment, Computers and Other Electronic Equipment, the fossil energy consumption per unit of output of the year 2009, 2010, and 2011 is respectively 0.63 ton standard coal per million Yuan, 0.54 ton standard coal per million Yuan and 0.03 ton standard coal per million Yuan, and the carbon emission intensity of the three years respectively 0.4 ton/million Yuan, 0.33 ton/million Yuan and 0.02 ton/million Yuan. Among all manufacturing industries this set of figures is relatively the smallest and shows a decreasing trend. At the same time, Manufacture of Communication Equipment, Computers and Other Electronic Equipment has the largest number of patents, so it is fair to say that it has the highest technological efficiency along with a favorable institutional environment.

Manufacturing industries with overall technical efficiency between 0.8-1 are of relatively high performance, including: Manufacture of Non-metallic Mineral Products, Manufacture of Measuring Instruments and Machinery for Cultural Activity and Office Work, Manufacture of Electrical Machinery and Equipment, Manufacture of Artwork and Other Manufacturing, Processing of Petroleum, Coking, Processing of Nuclear Fuel, Manufacture of Special Purpose Machinery, Manufacture of Tobacco, Manufacture of Raw Chemical Materials and Chemical Products, and Manufacture of General Purpose Machinery. Manufacture of Non-metallic Mineral Products is one of the sunrise industries in modern society where high technology and low environmental impact have become the development tendency. Manufacture of Measuring Instruments and Machinery for Cultural Activity and Office Work and Manufacture of Electrical Machinery and Equipment have relatively high levels of innovation input and output.

Manufacturing industries with overall technical efficiency between 0.7-0.8 are of common performance, including: Manufacture of Articles For Culture, Education and Sport Activities, Manufacture of Chemical Fibres, Smelting and Pressing of Non-ferrous Metals, Manufacture of Beverages, Manufacture of Furniture, Printing, Reproduction of Recording Media, Manufacture of Textile Wearing Apparel, Footware and Caps, Manufacture of Metal Products Manufacture of Transport Equipment, Manufacture of Foods, Manufacture of Leather, Fur, Feather and Related Products, Manufacture of Textile, and Processing of Food from Agricultural Products. This paper mainly analyzes Manufacture of Foods and Manufacture of Textile, both of which are sunset industries (Li, 2013). Their innovation input and output are in a weak position. And they have problems such as the gradual loss of labor, raw material and other cost advantages, environmental pollution, ecological destruction, etc.

Manufacturing industries with overall technical efficiency lower than 0.7 are of common performance, including Manufacture of Rubber, Manufacture of Plastics, Manufacture of Paper and Paper Products, Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products, and Manufacture of Medicines. This paper mainly analyzes Manufacture of Rubber and Manufacture of Plastics. The reason for their low performance is that they are high-polluting industries. It can be seen from the factor score table that the innovation resource input is relatively inadequate. Both Manufacture of Communication Equipment, Computers and Other Electronic Equipment and Manufacture of Medicines are high and new technology industries strongly supported by the Chinese government, but the low-carbon technological innovation ability of Manufacture of Communication Equipment, Computers and Other Electronic Equipment is significantly better than that of Manufacture of Medicines.

In terms of the trend analysis, both overall technical efficiency and pure technical efficiency are improved while scale efficiency slightly declines. It is also proven that scale efficiency is the reason why overall technical efficiency growth is lower than pure technical efficiency growth. The overall technical efficiency of China's manufacturing industries is quite different; the technical efficiency is not high. The average technical efficiency of 29 manufacturing industries is 0.791, which indicates a potential decrease of innovation input resources by 21.9% at most after rational allocation of resources, under the premise of not reducing current output. This reflects not only the relatively low technical efficiency of low-carbon technological innovation of China's manufacturing industry under the GVC, but also a large room for improvement in competitiveness of China's manufacturing industry.

5.2. The impact of the main factors on innovation performance

(1) The influence of market pulls on low-carbon technological innovation performance

The influence coefficient of market pull to low-carbon technological innovation performance of China's manufacturing industry under the GVC is 1.65E-08 (as shown in Table 4). Market pull does not have significantly positive and effective impacts on low-carbon technological innovation performance of China's manufacturing industry under the GVC. On the one hand, it shows that current market demand for low carbon products (technology, service) is quite small, as well as that most of China manufacturing industry's low-carbon products (technology, service) still aim for the domestic market instead of the global market. On the other hand, it indicates the weak R&D ability of manufacturing industry's low-carbon technology and the inadequate international marketing of low-carbon products (technology, service).

(2) The influence of technology push on low-carbon technological innovation performance

It can be seen from Table 4 that the influence coefficient of technology push to low-carbon technological innovation performance of China's manufacturing industry under the GVC is -0.008008, which shows that technology push has a negative influence on low-carbon technological innovation performance. This is mainly because that the contribution rate of technology push does not keep rising year by year, which is meanwhile influenced by the coordination of labor and capital resource. In addition, the development of science and technology requires long-term reserve, thus the influence of technology push on low-carbon technological innovation performance is lagged and chronic. The finding also verified Wang's (2005) analysis of China's technology push in development and production and that in environmental protection, the result of which is that the mismatching of these two types of technology push in content, level, speed and scale will exert a negative influence on social economic function of the technology push itself.

(3) The influence of government regulation on low-carbon technological innovation performance

The influence coefficient of government regulation of low-carbon technological innovation performance is 0.000162. Each additional one percentage of government regulation will lead to an increase in overall technical efficiency by 0.000162% (as shown in Table 4). On the whole, it is not very significant, which indicates that government's investment in technology does not effectively play its role as a guide. This is because the government's regulatory measures also depend on the expected reaction of manufacturing enterprises. Also information asymmetry leads to governance difficulties and higher regulatory costs. At this stage, government regulation will increase the production costs of enterprises and thus leads to a weak positive impact on the innovation activities of enterprises, which affect the implementation effect of regulatory policies and measures. At the same time, it also suggests that government financial support is still not strong enough.

6. Conclusion

In the context of the GVC, innovation performance of low-carbon technological innovation activities of China's manufacturing industry is quite low and shows no explicit increase. This is not the case for several low-carbon emerging industries in China. For example, China's solar photovoltaic (PV) industry saw a leapfrogging development in the past decade (Huang, et al., forthcoming). This situation implies that other than radical innovation and system transitions of a few emerging low-carbon technologies like solar PV, plenty of incremental and "normal" innovation activities of carbon reduction technologies widely exist in traditional industries. For a follower country like China, its manufacturing industry has long been embedded in and governed by the GVC. As a result, it requires a high profile of compatibility and flexibility for manufacturers, however, most of which seem hard to fit in to it so far. In general, the pure technical efficiency is higher than the scale efficiency, while the overall technical efficiency is low, which implies that there is a large room for competitiveness improvement for China's manufacturing industry. Moreover, the results also show that the low-carbon technological innovation performance is diverse across manufacturing industries. This finding calls for a focus on industry heterogeneity of innovation process of low-carbon technologies in manufacturing sector.

Government regulation, technology push, and market pull all shows no explicit impact on low-carbon technological innovation performance under the GVC, which could be the reason why innovation performance remains low. Government regulation shows a positive effect, however the weak impact is hardly detected. The results do not correspond to the previous empirical study on the determinants of eco-innovation by Horbach, et al. (2012), which evidenced the importance of current and expected government regulation and customer requirements. It is fair to say that when placing the low-carbon technological innovation activities under the GVC, the effect of government regulation, technology push, and market pull has not taken force yet, which might be induced by less attention on GVC governing of low-carbon innovation activities and global market of low-carbon products. This leads to a future research topic of the impact mechanism of government regulation, technology push, and market pull on low-carbon innovation activities in the context of GVC governance, which could involve cross-country technology transfer, guidance of global technical standard, and regional heterogeneity of technology legitimacy.

Based on the results, we found that overlooking the impact of GVC governance on low-carbon technological innovation activities is the main cause explaining why the three key pillars of low-carbon innovation (government regulation, technology push, and market pull) have not taken force yet. In this context, we urge the main actors of Chinese manufacturing industries, especially manufacturers and central and local governments, pay more attention to the force of GVC governance and make a better use of the GVC force: 1) to better utilize the international intelligence network of low-carbon knowledge and technologies, for example major manufacturers could set up new R&D center aboard to compete for more high-profile experts and engineers; 2) to better exploit the global commodity market, for example manufacturers could make better use of foreign direct investment, aiming for a better and cheaper access to foreign markets; 3) to better integrate local regulation and incentive policy that stimulate transnational technology import, for example central or local government could enhance the pollution and emission standard, and at the same time increase their support on key technology and equipment import by setting up special funding or subsidies.

Acknowledgments

The authors are grateful for the important and valuable comments of anonymous reviewers. This paper is funded by the National Natural Science Foundation of China as the General Program (Project No. 71472057, 71273073 and 71073041), MOST of China as the National Soft Science Program (Project No. 2012GXS4D080) and MOE of China as the Research Fund for the Doctoral Program of Higher Education (Project No. 20122304110026).

Appendix A

Subjects and coding

Appendix B

The raw data

Appendix C

Data processing and calculation

Reference

Bai, J.J., Jiang, K.S., Li, J., et al., 2009. Analysis of the Impact of Environment Factors on Regional Innovation Efficiency: Empirical Test Based on the DEA-Tobit Two step Method. R&D Management, 21(2), 96-102. (In Chinese)

Breukers, S., Hisschemöller, M., Cuppen, E., et al., 2014. Analysing the past and exploring the future of sustainable biomass. Participatory stakeholder dialogue and technological innovation systems research. Technological Forecasting and Social Change, 81, 227-235.

Banker, R.D., Charnes, A., Cooper, W.W., 1984. Some models for estimating technical and scale inefficiencies in data envelopment analysis. Management Science, 30, 1078-1092.

Bergek, A., Jacobsson, S., Carlsson, B., et al., 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37(3), 407-429.

Bi, K.X., Huang, P., and Ye, H., 2015. Risk identification, evaluation and response of low-carbon technological innovation under the global value chain: A case of the Chinese manufacturing industry. Technological Forecasting and Social Change, 100, 238-248.

Bi, K.X., Wang, X.X., 2014. Study on the Performance of Chinese Manufacturing Low-carbon Technology Innovation in the Global Value Chain. 2014 International Conference on Industrial Engineering and Engineering Management (IEEM).

Chen, K., Guan, J., 2012. Measuring the efficiency of China's regional innovation systems: application of network data envelopment analysis (DEA). Regional Studies, 46(3), 355-377.

Chen, Y., Liu, B., Shen, Y., et al., 2016. The energy efficiency of China's regional construction industry based on the three-stage DEA model and the DEA-DA model. KSCE Journal of Civil Engineering, 20(1), 34-47.

Chiarolla, C., 2008. Institutional aspects of low carbon technology strategies for green innovations and their diffusion. Yale/UNITAR Global Conference On Environmental Governance and Democracy, September, 4-9.

Cole, M.A., Elliott, R.J., and Shimamoto, K, 2005. Industrial characteristics, environmental regulations and air pollution: an analysis of the UK manufacturing sector. Journal of Environmental Economics and Management, 50(1), 121-143.

Cruz-Cázares, C., Bayona-Sáez, C., and García-Marco, T. (2013). You can't manage right what you can't measure well: Technological innovation efficiency. Research Policy, 42(6), 1239-1250.

Du, S.Y., 2008. Comparison Analysis on the International Model of Haier, TCL and Galanz. Economy and Management, 22(7), 53-59 (In Chinese).

Feng, W.N., 2010. A Correlation analysis on High- tech Enterprise R&D Input and Innovation Output: the Experience Proof Come from High-tech Enterprises in Shandong Province. Economic Problems, (9), 74-78 (In Chinese).

Feng, Y.J. and Li, C.H., 1996. Analysis and reconstruction of the concept and measuring and calculating method of contribution rate of scientific and technological progress. China Soft Science, 9, 93-99 (In Chinese).

Gao, Y.H. and Wan, D.F., 2011. Firms'Ownership, Financing Source and R&D Output: Empirical Research on China's High-tech Industry. Science of Science and Management of S.&T., 32(9), 146-156 (In Chinese).

Geels, F., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy, 31(8–9), 1257-1274.

Geels, F. and Schot, J., 2007. Typology of sociotechnical transition pathways. Research Policy, 36(3), 399-417.

Gereffi, G., Humphrey, J., and Sturgeon, T., 2005. The governance of global value chains. Review of International Political Economy 12, 78-104.

Gereffi, G. and Korzeniewicz, M., 1994. Commodity chains and global capitalism. Praeger.

Gosens, J. and Lu, Y., 2013. From lagging to leading? Technological innovation systems in emerging economies and the case of Chinese wind power. Energy Policy, 60, 234-250.

Greene, W.H., 1981. On the asymptotic bias of the ordinary least squares estimator of the Tobit model. Econometrica: Journal of the Econometric Society, 505-513.

Hekkert, M., Suurs, R., Negro, S., et al., 2007. Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change, 74(4), 413-432.

Henriques, M.F., Dantas, F., and Schaeffer, R., 2010. Potential for reduction of CO2 emissions and a low-carbon scenario for the Brazilian industrial sector. Energy Policy, 38(4), 1946-1961.

Horbach, J., 2008. Determinants of environmental innovation-new evidence from German panel data sources. Research policy, 37(1), 163-173.

Horbach, J., Rammer, C., and Rennings, K., 2012. Determinants of eco-innovations by type of environmental impact-The role of regulatory push/pull, technology push and market pull. Ecological Economics, 78, 112-122.

Hu, J.B. and Gu, X.Y., 2006. Research on resource utilization and enterprise innovation. Studies in Science of Science, 1, 286-290 (In Chinese).

Huang, P., Negro, S., Hekkert, M., Bi, K.X. (forthcoming). How China became a leader in solar PV: an innovation system analysis. Renewable and Sustainable Energy Reviews.

Humphrey, J., 2004. Upgrading in global value chains. International labour office (ILO), 6-34.

Humphrey, J. and Schmitz, H., 2002. How does insertion in global value chains affect upgrading in industrial clusters? Comment est-ce que l'insertion dans des chaînes de valeur mondiales influe sur la revalorisation des regroupements industriels? 36, 1017-1027.
Hung, S. W. and Wang, A. P. (2012). Entrepreneurs with glamour? DEA performance characterization of high-tech and older-established industries. Economic Modelling, 29(4), 1146-1153.
Jacobsson, S. and Bergek, A., 2004. Transforming the energy sector: the evolution of technological systems in renewable energy technology. Industrial and Corporate Change, 13, 815-849.
Kaihua, C. and Mingting, K., 2014. Staged efficiency and its determinants of regional innovation systems: a two-step analytical procedure. The Annals of Regional Science, 52(2), 627-657.
Kaplinsky, R. and Morris, M., 2001. A handbook for value chain research. IDRC, 4.
Kiamehr, M., 2016. Paths of technological capability building in complex capital goods: The case of hydro electricity generation systems in Iran. Technological Forecasting and Social Change, in pressing.
Kirchhoff, B.A., Armington, C., Hasan, I., et al., 2002. The influence of R&D expenditures on new firm formation and economic growth. Washington, DC: National Commission on Entrepreneurship, 27, 4-24.
Kline, S.J. and Rosenberg, N., 1986. An overview of innovation. The positive sum strategy: Harnessing technology for economic growth, 275-305.
Klitkou, A. and Coenen, L., 2013. The emergence of the Norwegian solar photovoltaic industry in a regional perspective. European Planning Studies, 21(11), 1796-1819.
LööF, H., Heshmati, A., Asplund, R., et al., 2001. Innovation and performance in manufacturing industries: A comparison of the Nordic countries. SSE/EFI working paper series in economics and finance, 1-24.
Löschel, A. 2002. Technological change in economic models of environmental policy: a survey. Ecological economics, 43(2), 105-126.
Lan, Q.X., 2003. Management of global supply chain and strategic of improving international competitve. World Economy Study, 1, 20-23 (In Chinese).
Lee, K. and Yoon, B., 2015. The idiosyncrasy of research and development efficiency across types of small-and medium-sized enterprises: evidence from Korea. R&D Management, 45(3), 250-266.
Li, L.S., et al, 2013. 2013 Research report of chinese manufacturing development. 36-239 (In Chinese)
Liu Z, 2015. China's Carbon Emissions Report 2015. http://belfercenter.ksg.harvard.edu/files/carbon-emissions-report-2015-final.pdf.
MacGillivray, A., Jeffrey, H., Winskel, M., et al. 2014. Innovation and cost reduction for marine renewable energy: A learning investment sensitivity analysis. Technological Forecasting and Social Change, 87, 108-124.
Moon, H.S., 2013. The relative efficiency analysis of innovation activities with uncertainty: The case of Korean electronic equipment industry. Innovation, 15(3), 305-314.
Morrison, A., Pietrobelli, C., and Rabellotti, R., 2008. Global value chains and technological capabilities: a framework to study learning and innovation in developing countries. Oxford Development Studies, 36(1), 39-58.
Mudambi, R., 2007. Offshoring: economic geography and the multinational firm. Journal of International Business Studies, 38(1), 206.
NBS, 2010. The main data bulletin of the second inventory of national wide R&D resouece(NO.2)[EB/OL].
http://www.stats.gov.cn/tjsj/tjgb/rdpcgb/qgkjjftrtjgb/201011/t20101122_30483.html. (In Chinese)
Palm, F.C., Raymond, W., Mohnen, P., et al., 2004. An empirically-based taxonomy of Dutch manufacturing: innovation policy implications. MERIT-Infonomics Research Memorandum Series, MERIT, Maastricht:1-36.
Park, C.W., Kwon, K.S., Kim, W.B., et al., 2009. Energy consumption reduction technology in manufacturing—— A selective review of policies, standards, and research. International Journal of Precision Engineering and Manufacturing, 10(5), 151-173.
Pietrobelli, C. and Puppato, F., 2015. Technology foresight and industrial strategy. Technological Forecasting and Social Change, in pressing.
Pietrobelli, C. and Rabellotti, R., 2011. Global value chains meet innovation systems: are there learning opportunities for developing countries?. World Development, 39(7), 1261-1269.
Rennings, K., 2000. Redefining innovation—eco-innovation research and the contribution from ecological economics. Ecological Economics, 32(2), 319-332.
Rennings, K. and Rammer, C., 2011. The impact of regulation-driven environmental innovation on innovation success and firm performance. Industry and Innovation, 18(3), 255-283.
Schumpeter J A., 1934. The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle. New Jersey, U.S.: Transaction Publishers, 1934.
Schmitz, H., 2004. Local upgrading in global chains: recent findings. Institute of Development Studies. Sussex, 6,

2-7.
Smith, A., Voß, J., and Grin, J., 2010. Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. Research Policy, 39(4), 435-448.
Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge: Cambridge University Press.
Su, J. and Liu, J., 2012. Exploring critical factors in China's manufacturing technology innovation: Based on a case study from CNR Dalian. Journal of Knowledge-based Innovation in China, 4(2), 104-117.
Tavoni, M., De Cian, E., Luderer, G., et al., 2012. The value of technology and of its evolution towards a low carbon economy. Climatic Change, 114(1), 39-57.
Tobin, J., 1958. Estimation of relationships for limited dependent variables. Econometrica: Journal of the Econometric Society, 24-36.
UNIDO, 2003. Industrial development report 2002/2003 competing through innovation and learning. United Nations Industrial Development Organization, 3-112.
Uyarra, E., Shapira, P., and Harding, A., 2016. Low carbon innovation and enterprise growth in the UK: Challenges of a place-blind policy mix. Technological Forecasting and Social Change, 103, 264-272.
Valadkhani, A., Roshdi, I., and Smyth, R., 2016. A Multiplicative Environmental DEA approach to measure efficiency changes in the world's major polluters. Energy Economics, 54, 363-375.
Van Alphen, K., Noothout, P. M., Hekkert, M. P., et al., 2010. Evaluating the development of carbon capture and storage technologies in the United States. Renewable and Sustainable Energy Reviews, 14(3), 971-986.
Wang, G.Y., 2005. On the Asymmetry of Science and Technology Progress. Studies In Dialectics of Nature, 21(6), 80-83 (In Chinese).
Wang, Q.Y., 2003. Chinese energy efficiency and international comparasion. Conservation and Environmental Protection, (8), 5-7 (In Chinese).
Woerter, M., 2009. Industry diversity and its impact on the innovation performance of firms. Journal of Evolutionary Economics, 19(5), 675-700.
Wu, Z.L. and Mu, R.P., 2005. Analysis of competitiveness of Chinese communication equipment manufacturing. Science of Science and Management of S.&T., 3, 83-87 (In Chinese).
Yang, F. and Yang, M., 2015. Analysis on China's eco-innovations: Regulation context, intertemporal change and regional differences. European Journal of Operational Research, 247(3), 1003-1012.
Yang, J.J., et al, 2011. Research on Relationship between Market Power and Independent Innovation Performance: Take Telecommunication Industry as an Example. Science of Science and Management of S.&T., 32(9), 65-72 (In Chinese).
Zhang, J.C., 2001. Method of using export data to evaluate international competitiveness. Economic Management, (20), 17-25 (In Chinese).
Zhang, F. and Gallagher, K.S., 2016. Innovation and technology transfer through global value chains: Evidence from China's PV industry. Energy Policy, 94, 191-203.