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RESEARCH ARTICLE

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Trends and driving forces of low-carbon energy technology innovation in China's industrial sectors from 1998 to 2017: from a regional perspective

Abstract Low-carbon energy technology (LC) innovation contributes to both environmental protection and economic development. Using the panel data of 30 provinces/autonomous regions/municipalities in China from 1998 to 2017, this paper constructs a two-layer logarithmic mean Divisia index (LMDI) model to uncover the factors influencing the variation of the innovation of LC in China's industrial sectors, including the alternative energy production technology (AEPT) and the energy conversation technology (ECT). The results show that China's industrial LC patent applications rapidly increased after 2005 and AEPT patent applications outweighed ECT patent applications all the time with a gradually narrowing gap. Low-carbon degree played the dominant role in promoting the increase in China's industrial LC patent applications, followed by the economic scale, R&D (research and development) efficiency, and R&D share. Economic structure contributed to the increases in LC patent applications in the central and the western regions, while led to the decreases in the eastern region, the north-eastern region, and Chinese mainland[1)]. Low-carbon degree and economic scale were two main contributors to the growths of both industrial AEPT patent applications and ECT patent applications in Chinese mainland and the four regions. Several policy recommendations are made to further promote industrial innovation in China.

Keywords low-carbon energy technology (LC), logarithmic mean Divisia index (LMDI), industrial sector, regional disparity, China

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1 Introduction

Technology innovation plays an essential role in promoting sustainable economic development [1]. In recent years, developing low-carbon energy technologies has attracted an increasing attention all over the world as such technologies contribute to both environmental protection and economic development [2]. Climate change is now one of the major global environmental problems and requires more innovative energy policies because both the economy and natural ecosystems are increasingly threatened by the greenhouse gases effect. The increasing energy demand and fossil fuel-based energy consumption structure have been widely recognized as the main causes of climate change [3]. Technology innovation, including promoting energy efficiency and optimizing energy structure, is

1) Xizang (Tibet) Autonoomous Region is not considered due to lack of data. The same below.

effective in facilitating the transition toward a low-carbon society.

International organizations, including the International Energy Agency (IEA), United Nations Environment Programme (UNEP) and Organization for Economic Cooperation and Development (OECD), initiated several programs in fostering energy technology innovation [4], such as the "Green Growth and Eco-innovation" project launched by the OECD in 2008. Besides, China is making great efforts to promote the low-carbon energy technology (LC) innovation, which has become an important part of ecological civilization construction proposed by the central government. As the largest energy consumer, China's industrial sectors have paid special attention to energy technology innovation and increased research budget, in order to accelerate the construction of a cleaner production system under the pressure of various environmental regulations [5]. According to China's Intellectual Property Office, almost all of the innovation activities of the alternative energy production technology and the energy conservation technology (ECT) are concentrated upon the industrial sectors. Therefore, to better understand the innovation situation of low-carbon energy technologies and raise effective promotion policies, this paper chooses China's industrial sectors as the research object.

The LC mainly arises from industrial production activities and generally consists of two types, i.e., energy structural optimization and energy efficiency improvement. Energy structural optimization is to encourage the application of renewable energy or low-carbon fossil fuels for industrial production, while energy efficiency improvement is to widely promote the energy efficient technologies and equipment [4]. There are three kinds of indicators for the measurement of technological innovation, i.e., R&D investment, the number of patents, and the total factor productivity [6]. R&D investment and the total factor productivity have some drawbacks because they cannot be subdivided into specific green technological areas. The number of patents is widely used as a proxy variable of technology innovation. There is a strong correlation and almost no lag between patent applications and R&D investment [7]. Thus, many studies use the number of patents to denote technological innovation, such as Albino et al. [4], Wang and Zhao [6], Fujii and Managi [8].

According to the International Patent Classification (IPC) green inventory, the green technology inventions in terms of energy fields are comprised of alternative energy production technology innovation and ECT innovation [8]. China is a large country with imbalanced development. This means that the industrial innovation in different Chinese provinces/autonomous regions/municipalities are very different due to different economic development stages, research strengths, and culture [9]. Hence, it is necessary to investigate the disparity of LC innovations in China's different regions.

Academically, many studies have been conducted to investigate the development of green technologies, especially in developed countries. For example, Brunnermeier and Cohen [10] explored the determinants of environmental innovation in US manufacturing industries. Popp [11] uncovered the effects of NO_x and SO_2 regulation on air pollution control technologies in the US, Japan, and Germany. Corsatea [12] studied the technological capabilities for innovation activities across Europe. Fujii and Managi [13] explored the environmental technology in Japan's private and public sectors. Cho and Sohn [14] analyzed the main factors driving green patent applications in France, Germany, Italy, and the UK. It is found that the US and Germany have developed more green technologies than others. It is also found that private and public sectors have different environmental patent applications. Besides, Jordaan et al. [15] studied the energy technology innovation in Canada and found that clean energy technology innovation can significantly reduce greenhouse gas emissions. However, only a few studies focus on green technologies in emerging economies. In this regard, Lubango [16] explored the trends of green inventions in three developing countries, including Brazil, India, and South Africa. Montenegro et al. [17] identified the specific scientific and technological areas that fostered environmental technological development in 1990, 2000, and 2010 in BRICS countries, including Brazil, Russia, India, China and South Africa.

Regarding China, Sun et al. [18] studied the pattern of patent-based environmental technology innovation in China and found that most environmental patents were applied by eastern provinces/autonomous regions/municipalities. Tan [19] studied the life cycle of clean technology R&D in China and found that the public sector plays a dominant role. Fujii and Managi [8] studied the sustainable green technology inventions in China and found that R&D effort and the prioritization of sustainable green patents are important drivers. Several related studies examined the historical trends of China's patent growth. For example, Chen et al. [9] studied the eco-innovation and influencing factors in China. Chen et al. [20] studied the technological progress using the panel stochastic frontier model in 30 provinces/autonomous regions/municipalities in China over 1989–2014. Chen and Zhang [21] studied the types of patents and driving forces behind the patent growth in China. However, none of the above studies investigated the development of LC innovation in China's industrial sectors, especially focusing on regional disparities among different provinces/autonomous regions/municipalities. As such, the driving forces in China's industrial LC development have scarcely been investigated. In fact, industrial sectors are playing important roles in emission mitigation and technology development. Consequently, it is crucial to uncover the trends of LC innovations and their driving forces in China's industrial sectors from a region-level perspective so that effective regional policies can be made to guide green innovation.

With regard to the research methodology, the decomposition framework is frequently used for the analysis of driving forces. Fujii [22] applied the logarithmic mean Divisia index (LMDI) method to decompose patent data of green chemical technology inventions in Japan although only two influential factors were considered, i.e., the priority of a specific technology and the scale of all technology inventions. Fujii and Managi [13] extended their LMDI method to further include four driving factors of Japan's environmental technology development, i.e., the priority of a specific environmental technology, the importance of environmental technology, the efficiency of patents based on R&D expenditures, and the scale of R&D activities. Later, Fujii and Managi [8] took the scale of economic activity into account based on their LMDI method [13]. However, the LMDI method proposed in all the above studies is a one-layer decomposition model and the data used for this model are time-series, containing less information and lower accuracy than a two-layer decomposition model, which used panel data [23]. In addition, the economic structure factor is not considered in the one-layer decomposition model. Therefore, it is crucial to include more important factors in a newly constructed decomposition framework for exploring the driving forces of LC innovation in China's industrial sectors.

To fill such a research gap, this paper first examined the innovation trends of LC in China's industrial sectors from 1998 to 2017. Then, it applied the logarithmic mean Divisia index (LMDI) method to uncover the factors influencing the variation of innovation trends from regional perspectives. Finally, it evaluated regional contributions to the variations of national innovation. This paper uncovered the trend of LC innovation in China's industrial sectors so that useful insights could be provided for preparing China's industrial innovation policies. Besides, it constructed a two-layer LMDI decomposition model to examine the driving forces of LC innovation, not only focusing on the effects from technology priority, low-carbon degree, R&D efficiency, R&D share, and economic scale, but also emphasizing the economic structure effect to examine the impact of regional disparity of economic development on LC innovation. Moreover, it uncovered regional disparities in terms of LC innovation in China's industrial sectors so that region-specific policies could be made by considering the local realities.

2 Methods and data

2.1 LMDI method

The decomposition analysis technique has been frequently used in energy and environmental studies in recent decades [23]. Two main decomposition analysis methods, i.e., index decomposition analysis (IDA) and structural decomposition analysis (SDA), have been developed. While the SDA method requires both input and output data for the analysis, the IDA method relies only on the total amount of inputs data, which makes it very effective for decomposition analysis of the model containing time series data or only several factors. To date, the IDA method has been widely applied to study the determinants of changes in research variables [24,25]. Among the IDA methods, the LMDI method proposed by Ang and his colleagues is widely accepted due to its characteristics of theoretical foundation, adaptability, ease of use, and result interpretation [26,27]. Therefore, a two-layer LMDI decomposition model is constructed in this paper to identify the driving factors of LC innovation, which is represented by the patent applications of China's industrial sectors.

Six indicators are considered in this paper, namely, the share of patent applications focusing on a specific LC in the total number of patent applications of LC (i.e., technology priority), the proportion of patent applications of LC to all patent applications (i.e., low-carbon degree), the efficiency of R&D expenditures in terms of patents (i.e., R&D efficiency), the ratio of R&D expenditure relative to the industrial output (i.e., R&D share), the proportion of industrial output in a specific province/autonomous region/municipality to national gross industrial output (i.e., economic structure), and the scale of economic activity of one industrial sector (i.e., economic scale). These indicators are chosen as investigated factors of LC innovation because they reflect the economic and technological aspects which have been shown in previous studies to have played an important role in driving technological innovation. Other aspects, such as population, institution and policies, have insignificant or marginal effects on the direction of technological innovation in China [28]. In most of the related literature, R&D investment is regarded as an essential driving force for technological innovation [29]. Previous studies show that the increase in innovation input intensity will promote technological innovation and increase the innovation output of low-carbon energy [29]. Thus, R&D share is an important factor for LC innovation. Besides, economic scale and economic structure have important effects on technological innovation because economic activity is generally related to innovation activity [19]. As indicators of the efficiency of patent publication based on R&D expenditure and focus of technological innovation on specified energy innovation, R&D efficiency, low-carbon degree and technology priority also have significant effects on low-carbon energy innovation [19].

The two-layer LMDI decomposition model is established to identify the determinants of the changes in the number of patent applications of a specific LC. Here, the decomposition process is introduced using alternative energy production technology patents as an example. The number of patent applications of the alternative energy production technology (AEPT patent applications) is decomposed using Eq. (1).

$$P_{\mathrm{AEPT}} = \sum_{i=1}^{n} \frac{P_{\mathrm{AEPT},i}}{P_{\mathrm{LC},i}} \times \frac{P_{\mathrm{LC},i}}{P_i} \times \frac{P_i}{\mathrm{RD}_i} \times \frac{\mathrm{RD}_i}{Y_i} \times \frac{Y_i}{Y} \times Y$$
$$= \sum_{i=1}^{n} \mathrm{TP}_i \times \mathrm{TD}_i \times \mathrm{RE}_i \times \mathrm{RS}_i \times \mathrm{ES}_i \times Y, \quad (1)$$

where P_{AEPT} refers to the number of AEPT patent applications; i refers to China's provinces/autonomous regions/municipalities; and n refers to the total number of China's provinces/autonomous regions/municipalities. For China, n = 30; for China's eastern region, n = 10; for China's central region, n = 6; for China's western region, n = 11; for China's north-eastern region, n = 3. The definitions of other variables in Eq. (1) are listed in Table 1.

Based on Eq. (1) and the principle of the LMDI method, the effects of these six factors on the changes of AEPT patent applications can be obtained, whose detailed calculation process is presented in Electronic Supplementary Material (ESM).

The decomposition process of the number of patent applications of the ECT is similar to that of AEPT patent applications. For the total number of patent applications of LC (LC patent applications), it can be decomposed as

$$P_{\mathrm{LC}} = \sum_{i=1}^{n} \frac{P_{\mathrm{LC},i}}{P_i} \times \frac{P_i}{\mathrm{RD}_i} \times \frac{\mathrm{RD}_i}{Y_i} \times \frac{Y_i}{Y} \times Y$$
$$= \sum_{i=1}^{n} \mathrm{TD}_i \times \mathrm{RE}_i \times \mathrm{RS}_i \times \mathrm{ES}_i \times Y. \quad (2)$$

The calculation process of the five effects on changes of LC patent applications is similar to that of AEPT patent applications.

Overall, the theoretical contribution of this paper is to clarify the effect of regional heterogeneity on LC innovation in China's industrial sectors by constructing a two-layer LMDI decomposition model. In particular, the factor of provincial economic structure is introduced into the patent decomposition model. Other relevant studies [13,15,22] do not include the factor of provincial economic structure because of the limitations of the one-layer LMDI model. Such novelties facilitate this paper to distinguish regional impacts and regional disparities on the national LC innovation.

2.2 Data

Based on the data availability, the related data of China's 30 provinces/autonomous regions/municipalities from 1998 to 2017 are collected. Some districts of China including Hong Kong SAR, Macao SAR, Tibet Autonomous Region and Taiwan Province are not considered due to the lack of complete data in China's statistical yearbooks. Thus, 30 provinces/autonomous regions/municipalities in China are considered following Refs. [30,31]. According to the classification principle currently implemented by China's National Bureau of Statistics which has been frequently used in the existing studies (such as Zhang et al. [32] and Lin et al. [33]), the 30 provinces/autonomous regions/municipalities are further classified into four economic zones, as listed in Table B1 (ESM).

The total patent applications for China's industrial sectors are obtained from *China Statistical Yearbooks on Science and Technology*. The patent applications of LC (including AEPT) are derived from the database of China's Intellectual Property Office, combined with the IPC green inventory provided by the World Intellectual Property Organization (WIPO). According to the IPC green inventory, the alternative energy production technology can be divided into 13 main categories and ECT can be divided into seven main categories (see Table B2, in ESM).

The data of industrial output values are taken from *China Industry Statistical Yearbooks*. The raw data at the current prices are deflated to constant 2000 prices through the industrial producer price indices for industrial products. The R&D expenditure data are taken from *China Statistical Yearbooks on Science and Technology*. The R&D expenditure data are deflated to constant 2000 prices

Table 1 Definitions of variables in Eq. (1)

Variable	Determinant	Description	Item
TP_i	$P_{\mathrm{AEPT},i}/P_{\mathrm{LC},i}$	Technology priority	$P_{\mathrm{AEPT},i}$: patent applications of the alternative energy production technology in the industrial sector of ith province/autonomous region/municipality
TD_i	$P_{\mathrm{LC},i}/P_i$	Low-carbon degree	$P_{\mathrm{LC},i}$: patent applications of LC in the industrial sector of ith province/autonomous region/municipality
RE_i	P_i/RD_i	R&D efficiency	P_i: all patent applications in the industrial sector of ith province/autonomous region/municipality
RS_i	RD_i/Y_i	R&D share	RD_i: R&D expenditure in the industrial sector of ith province/autonomous region/municipality
ES_i	Y_i/Y	Economic structure	Y_i: industrial output value of ith province/autonomous region/municipality
Y	Y	Economic scale	Y: national gross industrial output value

by using the weighted average value of consumer price indices and investment price indices. Following Refs. [34,35], the coefficient of consumer price indices is 0.55 and that of investment price indices is 0.45. All the price indices are taken from *China Statistical Yearbooks*.

3 Results

3.1 Historical trend of LC innovation

Figure 1 presents the trend in patent applications relating to LC containing AEPT and ECT in China's industrial sectors from 1998 to 2017. Both numbers of AEPT and ECT patent applications experienced rapid growths in this period, especially after 2005. The number of AEPT patent applications increased with an annual average rate of 33.6%, while the number of ECT patent applications increased with an annual average rate of 46.4%. The number of AEPT patent applications outweighed that of ECT patent applications in all the years mainly resulting from China's increasing attention to promoting renewable energy sources, such as hydroelectric power, biomass energy, wind power, and solar power, in the *Medium- and Long-term Program for Renewable Energy Development* [36]. However, the percentage of ECT patent applications to that of AEPT patent applications increases from 12.9% to 73.8%, reflecting that the gap between the two technology innovations has been narrowed. The reason for this is that in recent years a series of energy-saving policies and programs have been carried out, including the Ten Key Projects, Buildings Energy Efficiency, Top-1000 Energy-Consuming Enterprises Program, Structural Adjustment/Small Plant Closures, and Appliance Standards and Energy-Efficiency Labels [37].

Totally, the number of patent applications of LC increased with an annual average rate of 36.7%. Its growth did not begin to be apparent until 2005, mainly because the central government emphasized energy saving and environmental protection and released many policies to achieve energy conservation and emission reduction goals after 2005. The share of LC patent applications in that of the total patent applications in China's industrial sectors increased from 1.02% in 1998 to 1.77% in 2000, followed by a decrease to 0.99% in 2004, and then a rapid increase to 4.45% in 2017. It can be seen that the importance of LC innovation has been largely improved with China's rapid economic growth and increased environmental protection awareness.

In terms of regional disparities among China's four regions, the trends of LC patent applications in the industrial sectors of these regions are further investigated. As shown in Fig. 2, the eastern region has the most LC patent applications, much more than other regions, with an annual average increase rate of 34.8%. The total LC patent applications in the other three regions only occupied less than half of that in the eastern region, and the percentage increased from 15.7% to 49.2% from 1998 to 2017. Of the other three regions, the central region has the most LC patent applications, followed by the western region, while the north-eastern region has the lowest number. As for the growth rate, the western region experienced the rapidest growth with an annual average rate of 47.1%, followed by the central region (42.5%), while the northeastern region had the lowest (36.4%). Especially, the eastern region began to have more LC patent applications after 2005, which was the earliest of the four regions. The other three regions began to have more LC patent applications after 2009. This indicates that the eastern region has played a leading role in green innovation with a more advanced environmental protection awareness. With regard to the share of LC patent applications in total patent applications,

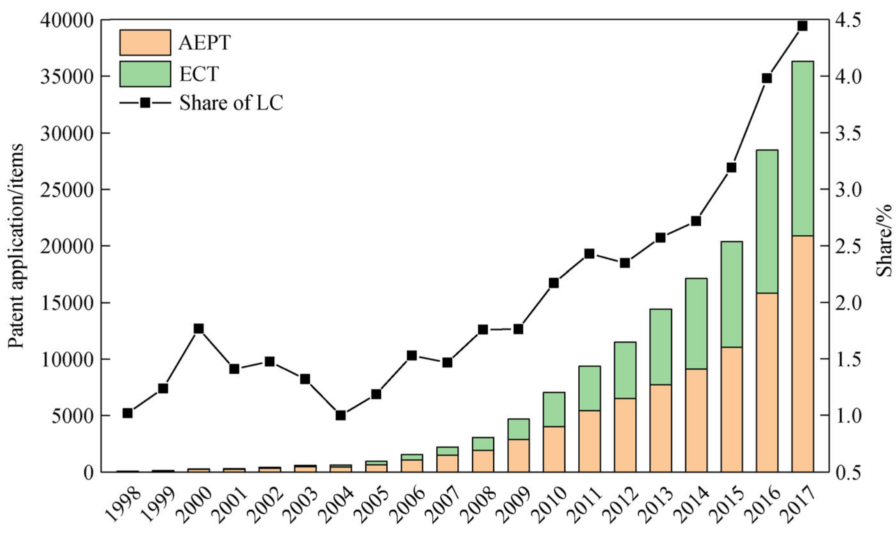

Fig. 1 Trends of patent application of LC and its share in total number of patent applications in China's industrial sector from 1998 to 2017.

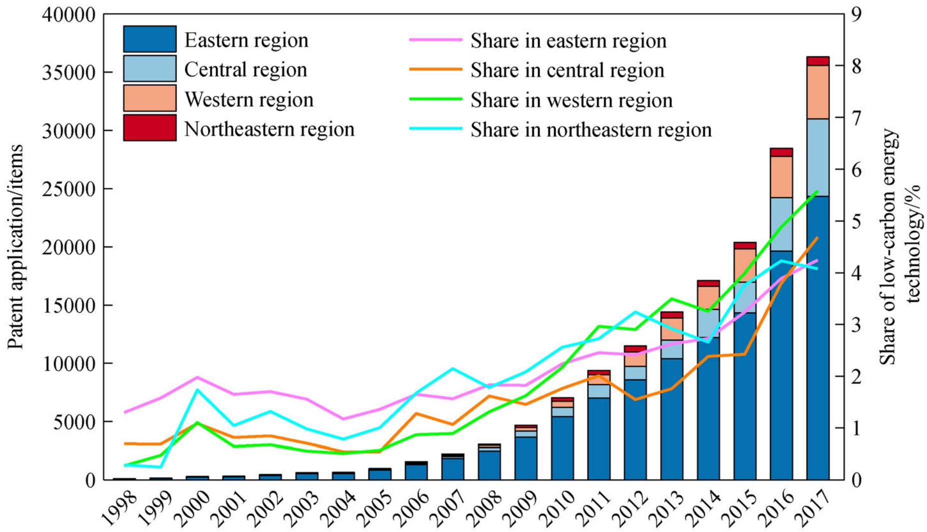

Fig. 2 Trends of patent application of LC and its share in total number of patent applications in industrial sector for China's four regions from 1998 to 2017.

such a share had the largest increase in the western region (from 0.3% in 1998 to 5.6% in 2017), followed by the central region (by 4.0%) and the northeastern region (3.8%), while the eastern region had the smallest increase (from 1.3% in 1998 to 4.2% in 2017).

3.2 Decomposition results of LC innovation

Figure 3 demonstrates the cumulative changes in AEPT patent applications and contributions of the six factors in China's industrial sectors, as well as its four regions. The values in Fig. 3 are based on the 1998 baseline. For Chinese mailand, low-carbon degree factor was the largest driver for the increase in AEPT patent application, which contributed to 48.2% of the increase from 1998 to 2017. Economic scale was the second largest factor, with a contribution rate of 25.7%, followed by R&D efficiency which contributed to 14.9% of the increase from 1998 to 2017. The effect of R&D share on AEPT patent applications had a volatile trend, which was positive from 1999 to 2005, followed by a negative trend from 2006 to 2011, and then a positive trend again from 2012 to 2017. In contrast, economic structure had an inhibiting effect on AEPT patent applications, with a contribution rate of –1.02% from 1998 to 2017. Besides, technology priority had a negative effect on AEPT patent applications in most years. But overall, the contribution of technology priority became positive (1.91%) during the entire period. Notably, the positive effect from the low-carbon degree factor was largely improved after 2015, reflecting that the China's industries started to apply renewable and sustainable energy sources and thus the incentives for low-carbon technology invention was highly promoted in recent years. Economic scale and R&D efficiency began to have obvious effects after 2009. China's economy was influenced by the global financial crisis in 2008. After that, the industrial production began to recover and the industrial financial performance was largely improved, which provided more financial support for technology innovation and patent applications [38]. Meanwhile, the innovation efficiency was also largely promoted due to the previous experience accumulation. R&D share began to have an obvious effect in 2010 and 2017 with opposite influencing directions, indicating that the proportion of R&D expenditure to industrial output was decreased in 2010 while largely increased in 2017. As a result, the total AEPT patent applications in China's industrial sectors increased by 20806 items from 1998 to 2017.

Among the four regions, the contributions of the six drivers to the changes of AEPT patent applications in the eastern region are similar to that of the whole Chinese mainland. In the eastern region, the low-carbon degree and economic scale were the most essential influencing factors, with contribution rates of 46.2% and 29.9%, respectively, followed by R&D efficiency (15.7%), while R&D share and technology priority had the least effects (8.5% and 1.5%, respectively) on the growth of AEPT patent applications from 1998 to 2017. In contrast, the economic structure inhibited the increase in AEPT patent applications by –2.9% in the entire period. In the central region, all the six factors contributed to the growth of AEPT patent applications in 2017, of which the effect low-carbon degree far outweighed those of others. The effects of low-carbon degree have been significantly improved since 2014, while the effects of R&D efficiency, R&D share, and economic scale turned to be obvious since 2009. The contribution rate of low-carbon degree from 1998 to 2017 was 53.2%, followed by economic scale (12.8%) and R&D share (12.1%), while R&D efficiency (9.1%), technology priority (7.2%), and economic structure (5.8%) had much

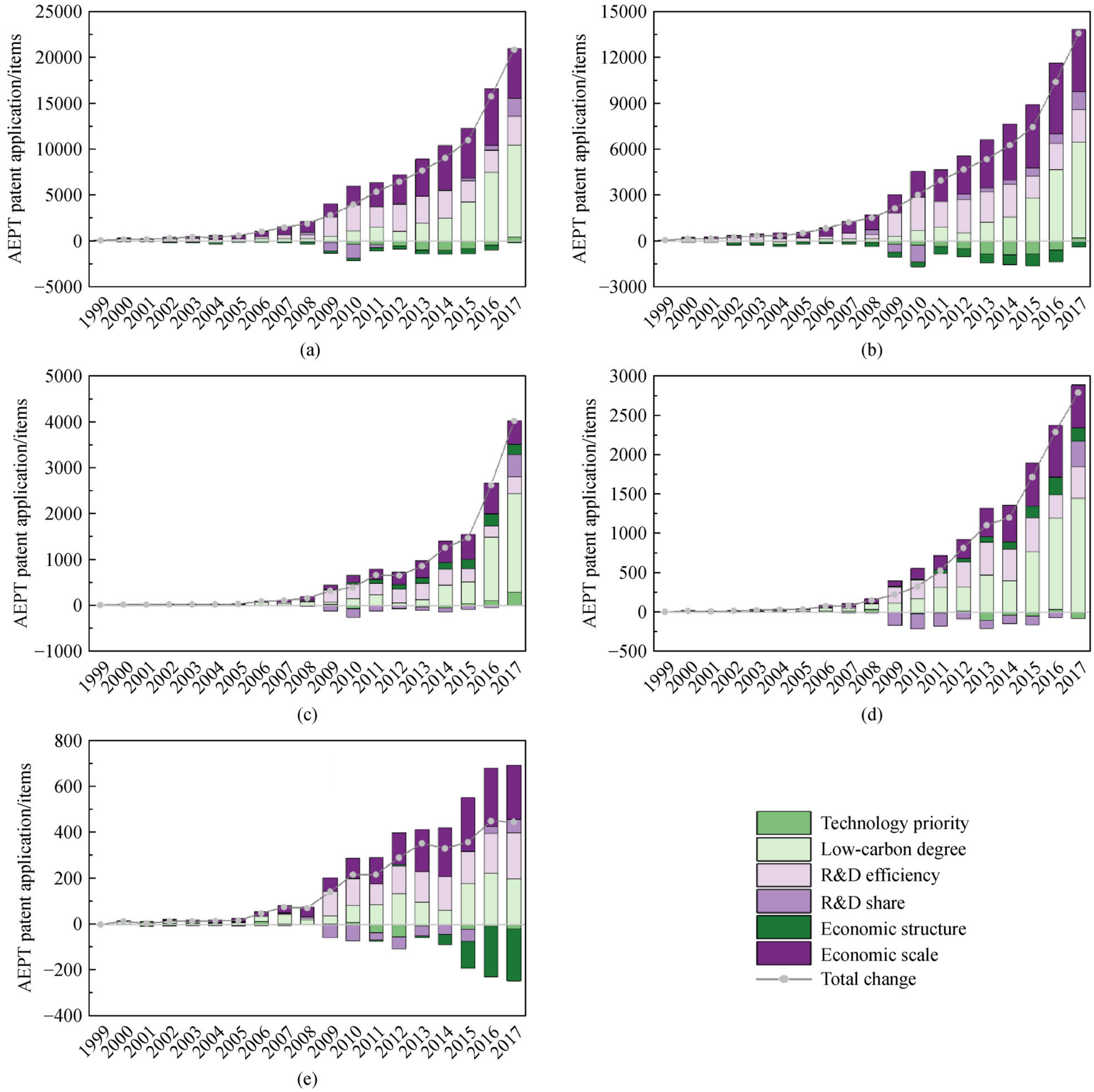

Fig. 3 Changes of AEPT patent applications and contributions of six factors in China's industrial sector from 1999 to 2017. (a) The whole Chinese mainland; (b) eastern region; (c) central region; (d) western region; (e) northeastern region.

smaller effects on the increase in AEPT patent applications. In the western region, all factors except technology priority contributed to the growth of AEPT patent applications from 1998 to 2017. The ranking of the positive effects in the western region is similar to that in the central region. Low-carbon degree played the dominant role (51.8%), followed by economic scale (19.4%), R&D efficiency (14.6%), and R&D share (11.5%), while economic structure had the small contribution (6.1%) to the increase in AEPT patent applications. In contrast, technology priority contributed to the decrease in AEPT patent applications by –2.9%. In the north-eastern region, economic scale, R&D efficiency, and low-carbon degree had crucial effects on the increase in AEPT patent applications in the entire period, with contributions of 52.7%, 44.8%, and 44.4%, respectively, while economic structure had an essential effect on the decrease in AEPT patent applications by contributing to –50.1%. The contributions from R&D share and technology priority were relatively small with values of 13.6% and –4.0%, respectively. Notably, the negative effect of economic structure was largely promoted from 2014 to 2017, which hindered the rapid growth pace of AEPT patent applications.

Figure 4 illustrates the decomposition results of the changes in ECT patent applications in China's industrial sectors, as well as its four regions. For Chinese mainland, low-carbon degree contributed the most to the increase (51.8%) while technology priority was the only factor for the decrease (–1.1%) in ECT patent applications from 1998 to 2017. This indicates that the technology emphasis shifted a little away from ECT to the alternative energy production technology while the total LC was largely improved in China's industrial sectors. Other factors including economic scale, R&D efficiency, R&D share, and economic structure contributed 24.4%, 12.8%, 11.5% and 0.3% to the increase in ECT patent applications, respectively. In the eastern region, economic structure and technology priority had the same contributions to the decrease in ECT patent applications (by –1.4%), while low-carbon degree played a major role in increasing the ECT patent applications (by 50.5%). The contributions of other factors in the eastern region were close to those of the whole Chinese mainland. In the central region, low-carbon degree contributed to 63.5% of the increase in ECT patent applications, and this effect became obvious in 2014. The contributions of economic scale and R&D share were 15.5% and 13.0%, respectively. R&D efficiency and economic structure had the least positive effects by contributing to 9.1% and 8.2%, respectively. The techno-

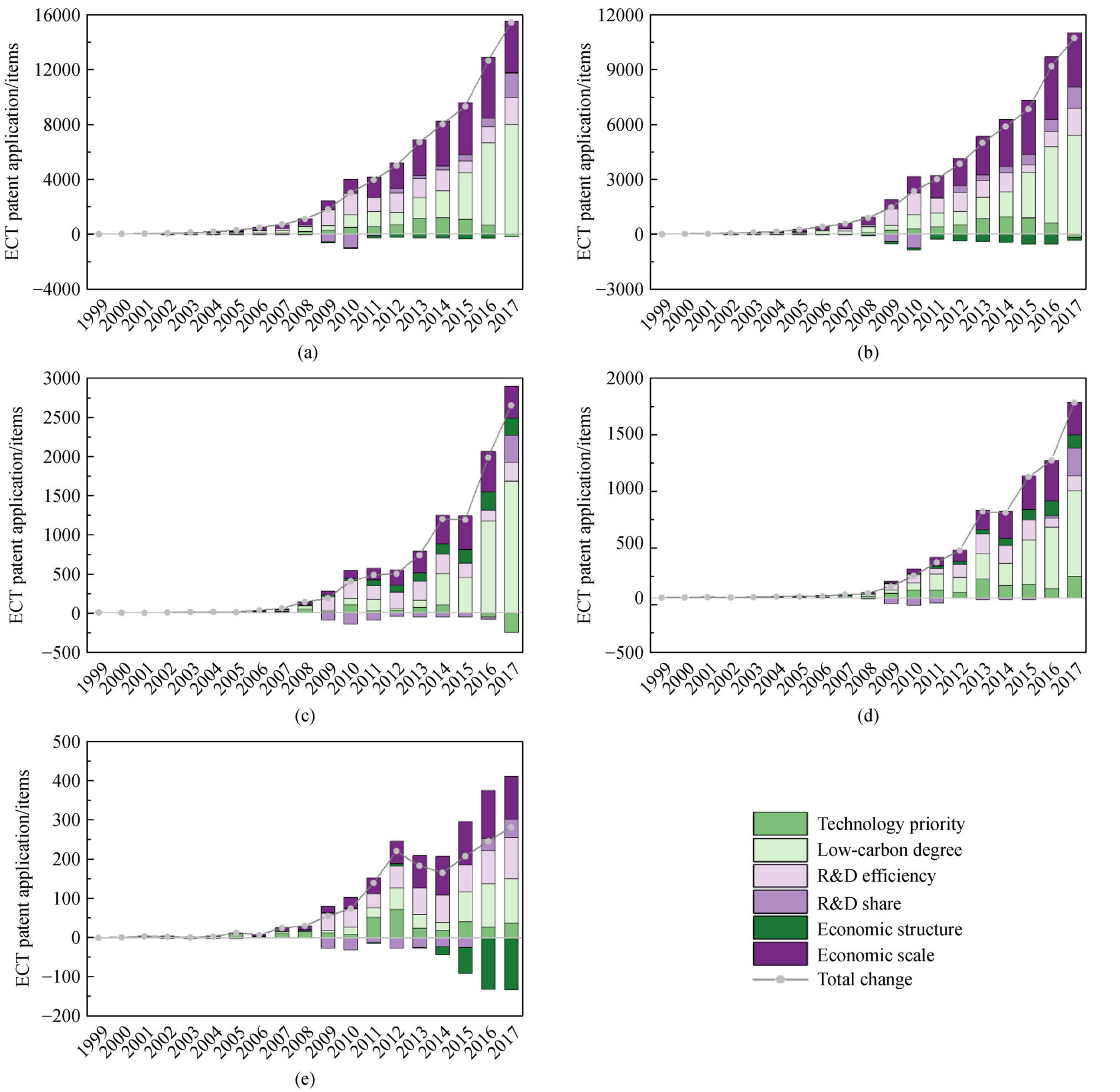

Fig. 4 Changes of ECT patent applications and contributions of six factors in China's industrial sector from 1999 to 2017. (a) The whole Chinese mainland; (b) eastern region; (c) central region; (d) western region; (e) northeastern region.

logy priority had a negative effect, by contributing –9.5% to ECT patent application changes. In the western region, all factors contributed to the increase in ECT patent applications and the effects began to be obvious after 2012, of which low-carbon degree had the largest effect (43.7%) while economic structure had the smallest one (6.6%). In the northeastern region, economic structure had a large reduction effect on ECT patent applications (46.5%) due to the economic slump in recent years. Low-carbon degree, economic scale, and R&D efficiency had almost the same effect on the increase in ECT patent applications by contributing to 40.0%, 39.3%, and 37.0%, respectively.

Taking AEPT and ECT patent applications as a whole, the changes in LC patent applications, and the driving forces behind are explored, as presented in Fig. 5. For industrial sectors at the national level, all factors except economic structure contributed to the increase in LC patent applications. This is similar to the decomposition results of AEPT patent applications in China's industrial sectors. Low-carbon degree contributed 50.0% to the increase in LC patent applications from 1998 to 2017, followed by economic scale (25.3%), R&D efficiency (14.2%), and R&D share (10.4%). In contrast, economic structure caused the decrease in LC patent applications by contributing to –0.5%. In the eastern region, the effects of the five factors were similar to those for the whole

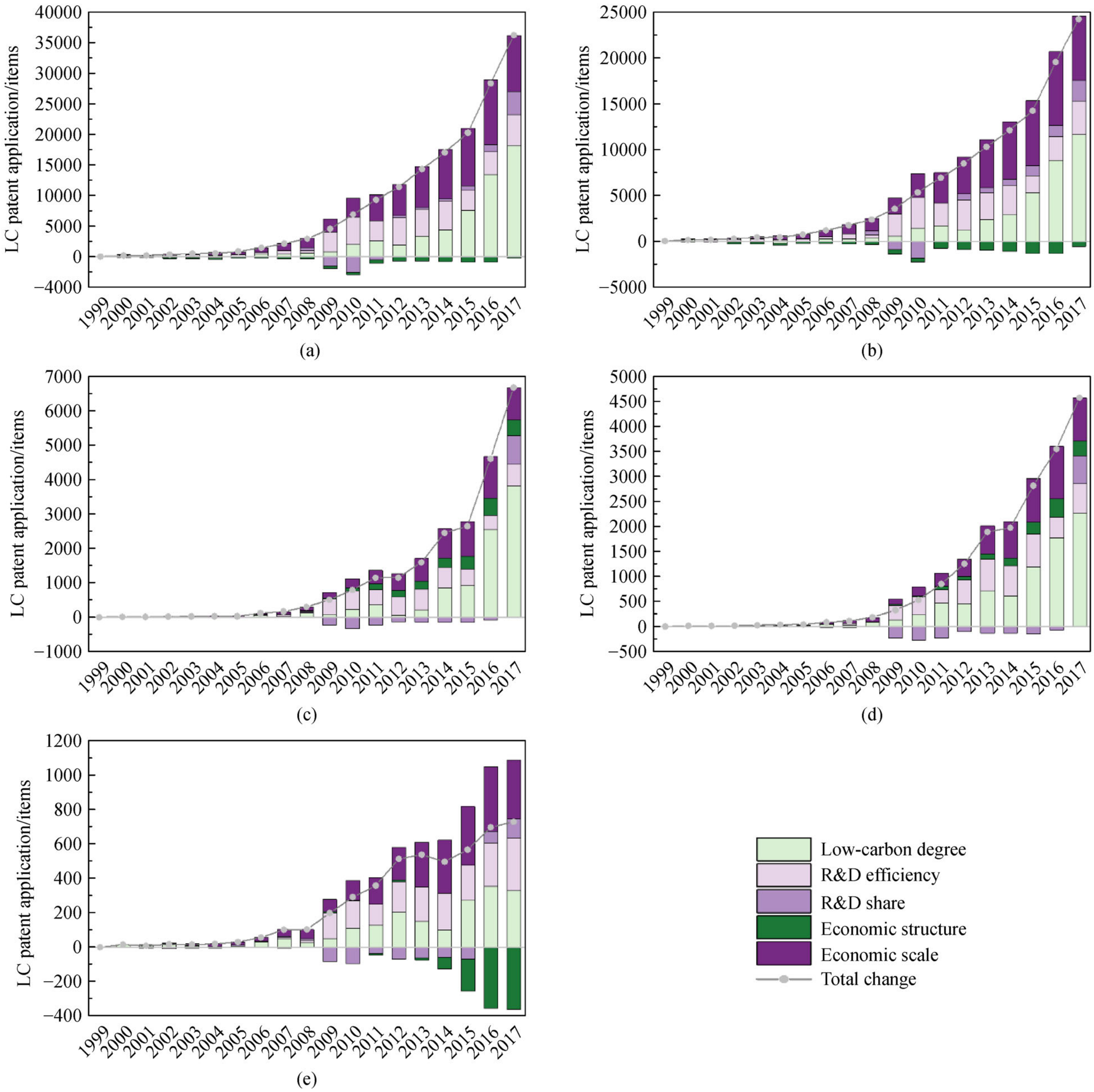

Fig. 5 Changes of LC patent applications and contributions of five factors in China's industrial sector from 1999 to 2017. (a) The whole Chinese mainland; (b) eastern region; (c) central region; (d) western region; (e) northeastern region.

country. The largest contributor to the increase in LC patent applications was low-carbon degree factor (by 48.2%) while the smallest one was R&D share (by 9.4%). In the central and western regions, the decomposition results of LC patent application changes are similar, and are also close to the decomposition results of AEPT and ECT patent application changes in these two regions. All the five factors played positive roles in LC patent applications in the two regions. In the central region, low-carbon degree contributed 57.2% to the increase in LC patent applications, followed by economic scale (14.2%), and R&D share (12.4%), while R&D efficiency and economic structure had the smallest effects with contribution rates of 9.4% and 6.8%, respectively. In the western region, the largest contributor to the increase in LC patent applications also came from low-carbon degree (49.7%), followed by economic scale (18.8%), R&D share (12.8%), and R&D efficiency (12.2%), while economic structure had the smallest effect (6.4%). In the northeastern region, the effects of LC patent application changes are similar to those of AEPT and ECT patent application changes. Economic scale, low-carbon degree, and R&D efficiency contributed the most to the increase in LC patent applications, by 47.0%, 45.1%, and 41.6%, respectively. On the contrary, economic structure was the only factor for the decrease in LC patent applications by –49.6%.

Further, the contributions of the four regions to the variation of industrial LC innovation in Chinese mainland are also analyzed, as presented in Fig. 6. Overall, the low-carbon degree, R&D efficiency, R&D share, and economic scale in the eastern region as well as the low-carbon degree in the central and the western regions had crucial effects on the increase in AEPT, ECT, and LC patent applications in China's industrial sectors. In contrast, the economic structure in the eastern and the north-eastern regions had obvious effects on the decrease in AEPT, ECT, and LC patent applications in China's industrial sectors. For AEPT patent applications, technology priority in the eastern and the central regions contributed to the increase in AEPT patent applications. This indicates that these two regions have paid more attention to AEPT innovation rather than ECT innovation. On the contrary, the western and north-eastern regions focused more on ECT innovation, and thus the technology priority of these two regions increased ECT patent applications. The low-carbon degree in the eastern region played a dominant role in promoting both AEPT and ECT patent applications and thus the total number of LC patent applications, followed by that in the central and the western regions, while the low-carbon degree in the northeastern region had a marginal effect on LC innovation. From 1998 to 2017, the share of LC innovation in the total technology innovation increased from 1.0% to 4.4% in China's industrial sectors. Of all provinces/autonomous regions/municipalities, Jiangsu province in the eastern region experienced the largest growth in low-carbon degree by 22 times from 1998 to 2017. For R&D efficiency and R&D share, the contributions of the four regions were much smaller, but the ranking of effects was

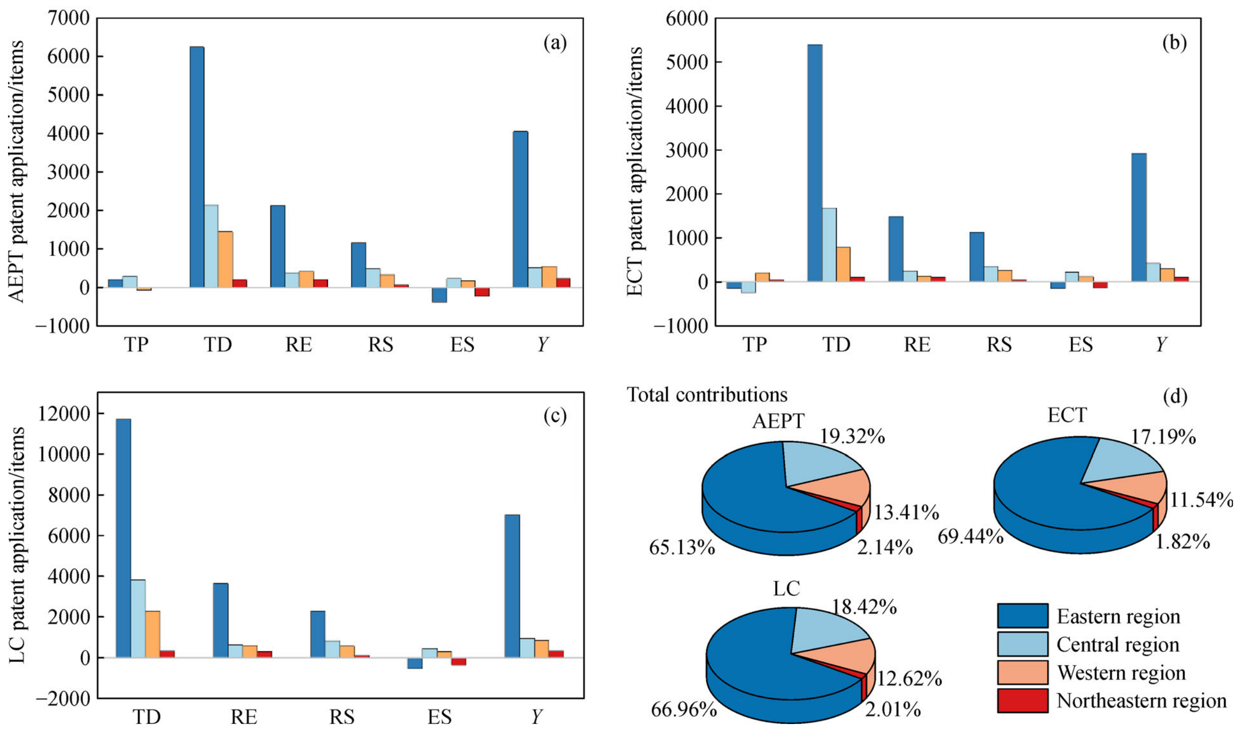

Fig. 6 Contributions of four regions to the changes of (a) AEPT, (b) ECT and (c) LC patent applications in industrial sectors of Chinese mainland from 1998 to 2017. (d) total contributions.

the same with that of low-carbon degree. Economic structure contributed to the increase in AEPT, ECT, and LC patent applications in the central and the western regions, mainly resulting from the improvement in industrial activity and output value in these two regions. The share of industrial output of the central region in the national industrial output had the largest growth from 15.0% to 18.6% from 1998 to 2017, while the share in the northeastern region had the largest decrease from 10.3% to 4.4% in the same period. The effect of economic scale had the largest contribution to the increase in AEPT, ECT, and LC patent applications in the eastern region, while the effects of economic scale were close but much smaller in the central and the western regions. Economic scale had the most marginal effect in the northeastern region. The reason for this is that the eastern region is the most developed region in China, followed by the central and the western regions, while economic development in the northeastern region is the slowest. From 1998 to 2017, the share of the eastern region in China's industrial output was above 60%, the shares of the central and the western region were 12%–19% and 10%–14%, while the share of the north-eastern region was below 10%. Research and development strategies depend on the corporate financial performance, and patent applications are associated with the application cost of patents, the running costs of experimental materials, and the costs of the salaries of researchers [8]. Thus, regional development has a positive correlation with patent applications in China.

As a result of all the effects from decomposed factors, the eastern region contributed the most to the increase in LC innovation in China's industrial sectors, with contribution rates of 65.13%, 69.44%, and 66.96% for AEPT, ECT, and LC patent applications, respectively, followed by the contributions of the central region (19.32%, 17.19%, and 18.42% for AEPT, ECT, and LC patent applications, respectively) and the western region (13.41%, 11.54%, and 12.62% for AEPT, ECT, and LC patent applications, respectively). However, the effects from the northeastern region were the smallest by contributing 2.14%, 1.82%, and 2.01% to AEPT, ECT, and LC patent applications, respectively.

4 Discussions and policy implications

Total patent applications of LC in China's industrial sectors increased by 36209 items from 1998 to 2017, with a growth over 97% from 2005 to 2017. China's national development planning documents clearly stated the necessity of developing green economy. The central government released several energy-saving policies or programs, including Ten Key Projects, Buildings Energy Efficiency Program, Top-1000 Energy-Consuming Enterprises Program, Structural Adjustment/Small Plant Closures, and Appliance Standards and Energy-Efficiency Labels [37]. Additionally, the low-cost and large-scale development and utilization of renewable energy sources were encouraged in the Medium- and Long-term Renewable Energy Development Program. Moreover, the Renewable Energy Law was enforced formally in 2006 [39]. The renewable energy sources which have been highly advocated include hydroelectric power, biomass energy, wind power, solar power, and geothermal power, etc. Furthermore, emissions standards were released to reduce pollutant emissions from industrial sectors [36]. To comply with these policies and programs, China's industrial companies began to widely apply renewable energy and energy conservation technologies.

Among the four regions, the eastern region played a dominant role in producing LC patent applications, mainly owing to the low-carbon degree of patent applications and the expansion of economic scale. The eastern region has the most developed modern industry in China, and the regional governments have paid more attention to mitigating the overall environmental impacts of their industrial production [40]. R&D activities are costly, considering the running costs of experimental materials, the relatively higher salaries of researchers, and patent application costs [19]. In this regard, the eastern region had the highest industrial output with more than half of the national gross industrial output, providing a strong financial support for the non-profit low-carbon technology innovation. Although the total LC patent applications in other regions were much smaller, the western region experienced the highest growth rate in the LC patent applications among the four regions, followed by the central region. The heavy industries which were characterized with a high energy consumption and high emissions shifted from the southeast coast to the central and western regions during the past years. However, green technology innovation was gradually accepted and implemented in the central and western regions to avoid becoming a "pollution paradise" [41]. The share of low-carbon innovation in total industrial innovation increased by 4.1% and 2.7% in the central and western regions from 1998 to 2017, respectively. Such a technology transfer combining with a steady economic growth made a great contribution to the increase in LC patent applications, leading to a rapid development of low-carbon technology in these two regions.

Among LC patent applications, the AEPT patent applications outweighed the ECT patent applications all the time, but the gap between the two gradually narrowed from 1998 to 2017. The reason for this is that the growth rate of ECT patent applications surpassed that of AEPT patent applications in that period. Low-carbon degree and economic scale were two main contributors to the growths of both AEPT patent applications and ECT patent applications in China's industrial sectors and the four regions. At present, China's economic development has entered into a "new normal" phase, but it is still necessary for the central government to keep economic growth within a reasonable range and continue to encourage the expansion of domestic demand. Meanwhile, industrial enterprises are expected to continue to increase their investment in LC innovation. In this regard, the central government should provide further support to facilitate LC innovation activities, strengthen the coordination and cooperation among different sectors and regions, and regularly assess these activities. However, the positive effects from R&D efficiency and R&D share on AEPT patent applications and ECT patent applications were much smaller from 1998 to 2017. It is therefore necessary to further improve these two factors by setting up appropriate policies. First, the central government should increase financial support for technology innovation and balance such research funds for related R&D activities. When the scale effect of governmental fund for the R&D activities in industrial enterprises is formed, there will be an improvement of technology innovation efficiency in industrial enterprises [42]. At the same time, regional disparity should be considered. Currently, the eastern region has a much stronger financial support for R&D due to its advanced economic development, while the local governments in the central, western, and northeastern regions have paid less attention to supporting such innovation activities. Therefore, the central government, especially the key funding agencies in Beijing, including the Ministry of Science and Technology and the National Natural Science Foundation of China, should formulate policies in supporting these less developed regions by setting up special research programs so that key technology issues in these regions can be solved. Besides, these less developed provincial and municipal governments should allocate more research funds in supporting related innovation projects, while the more developed eastern region should provide technology transfer to these regions so that they can improve their energy efficiency and optimize their energy structure quickly. In addition, foreign-invested industrial enterprises normally have better technologies and more advanced management experiences which can promote the use efficiency of production factors and the efficiency of technological innovation [43]. Their experiences should be transferred to other domestic enterprises. Moreover, international cooperation is also critical, from which the less developed regions can learn the most advanced knowledge and practices from international societies.

5 Conclusions

The role of energy technology innovation in reducing environmental emissions has been increasingly recognized worldwide, especially during the transition period toward more sustainable industrial development. R&D activities can significantly facilitate such industrial innovations in the transition process. Therefore, it is crucial to support more R&D activities so that more low carbon technologies can be promoted and applied, especially in developing countries where both financial support and R&D strength are weak. Using the panel data of 30 provinces/autonomous regions/municipalities in China from 1998 to 2017, this paper investigated the trend of LC innovation in China's industrial sectors and uncovered the related driving forces. Taking into account regional disparity, four regions in China were investigated in detail. A two-layer logarithmic mean Divisia index (LMDI) model was constructed to uncover the key factors influencing the variation of LC innovation both at national and regional levels.

The results showed that total LC patent applications in China's industrial sectors increased by 36209 items from 1998 to 2017, with a growth rate over 97% after 2005. Both AEPT and ECT patent applications experienced rapid growths, while AEPT patent applications outweighed ECT patent applications with a gradually narrowing gap. The eastern region had the most LC patent applications, much more than the central and the western regions, while the north-eastern region had the least applications. The share of LC patent applications in the total patent applications was largely improved in China's industrial sectors. The western region had the largest increase, followed by the central, the north-eastern, and the eastern regions.

The decomposition analysis results indicated that all the factors except economic structure contributed to the increase in LC patent applications in China's industrial sectors. Low-carbon degree played the dominant positive role, followed by economic scale, R&D efficiency, and R&D share. Economic structure contributed to the increases in LC patent applications in the central and the western regions, while led to the decreases in the eastern and the north-eastern regions. Low-carbon degree and economic scale were two main contributors to the growths of both AEPT patent applications and ECT patent applications in China's industrial sectors and the four regions. However, the positive effects of R&D efficiency and R&D share on AEPT patent applications and ECT patent applications were much smaller from 1998 to 2017. Regional disparity had a significant impact on the increase in China's industrial LC patent applications including AEPT and ECT patent applications. Low-carbon degree had a relatively small effect in the northeastern region while R&D efficiency, R&D share, and economic scale had a relatively small the effect in the central, the western, and the north-eastern regions, compared with other positive effects. Thus, the central government should pay more attention to these factors.

Based on the above findings, the research priorities and limitations of sustainable LC innovation in China's industrial sectors can be better understood. Several policy recommendations are proposed for low-carbon innovation improvement, including increasing financial support for technology innovation, attracting technology-oriented and environment-oriented foreign investment. Besides, regional balance in low-carbon innovation, and regional disparity should be taken into consideration so that different regions can better formulate their own innovation policies by considering the local realities. The local governments in the central, the western, and the northeastern regions should pay more attention to allocate more financial support for technology innovation. Technology transfer from the eastern region to other regions should be promoted to improve energy efficiency and optimize the energy structure in the less developed regions. Policy implications from this paper can provide valuable insights to other emerging countries facing similar low-carbon innovation needs.

However, this paper has several limitations. The first is the incomplete estimation of the regional patent data. The patent applications of some large companies are counted in places where their headquarters are located (like Shanghai and Beijing) despite of the fact that they may create patents in other places. This may have a minor effect on the data accuracy of the number of patents in different provinces/autonomous regions/municipalities. Moreover, due to the data availability, it is impossible to uncover the LC innovation in the sectors, such as the electricity production sector, the petroleum processing sector, the ferrous metals smelting and pressing sector, etc. Future research should be focused on such sub-sectors so that more appropriate policies can be prepared to encourage LC innovation in these sub-sectors.

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Notations

LMDI	Logarithmic mean Divisia index
LC	Low-carbon energy technology
AEPT	Alternative energy production technology
ECT	Energy conversation technology
IEA	International Energy Agency
UNEP	United Nations Environment Programme
OECD	Organization for Economic Cooperation and Development
IDA	Index decomposition analysis
IPC	International Patent Classification
WIPO	World Intellectual Property Organization

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