Decomposition analysis of sustainable green technology inventions in China

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Abstract: Sustainable green technology is an important contributor to creating a sustainable society by simultaneously promoting environmental conservation and economic development. This study examines the determinants of sustainable green technology invention in China, with a focus on the differences in green technology development priorities in each five-year plan period. This study uses patent publication data in a patent decomposition analysis framework. We find that sustainable green patent publications increased due to efficiency improvements, the prioritization of sustainable green patents, an increased R&D expenditure share and economic growth, especially during periods of gradual economic development in China. Additionally, we find that the relative priority of R&D shifted from renewable energy technology to pollution abatement and other sustainable green technology in the 12th five-year plan. The different R&D priority trends for sustainable green technologies among the five-year plans can be used to formulate effective policies that promote sustainable green technology invention.

Keywords: sustainable green technology, patent data, decomposition analysis, China

1. Introduction

Sustainable green technology (hereafter, green technology) is important to control pollutant emissions effectively and economically (UNCTAD, 2018). Green technology contributes to balancing environmental conservation and economic development, which is a key relationship for the creation of a sustainable society (Sun et al., 2008). The importance of green technology has increased worldwide, especially in China. According to Li (2017), the Chinese government is working toward 'Made-in-China 2025' to promote industrial capability due to innovation-driven manufacturing, industrial optimization, quality improvements, and green development.

Figure 1 presents the number and share of green technology patent (hereafter, green patent) publications from 1996 to 2015. The bars illustrate the number of patent publications by type of green technology based on the World Intellectual Property Organization (WIPO) environmental patent classification scheme. Figure 1 also shows the GDP growth rate in China. Until 2007, the GDP growth rate in China increased annually and reached approximately 14% in 2007. However, it dramatically declined in 2008 due to the global financial crisis triggered by the collapse of Lehman Brothers in 2008. After year 2008, GDP growth rate gradually decreased, and the GDP approached 6% in 2016.

The green line in Figure 1 shows the share of green patent publications to the total number of patent publications. This share decreased from 1996 to 1997 and gradually increased from 4.5% to 8.6% from 1997 to 2015. One interpretation of the low green patent share in the late 1990s is that incentives for green technology invention were lacking because such intellectual property right were considered less profitable than other patents, such as those on electric products and medicine, during a period of rapid economic growth (Fujii and Managi, 2016). Research and development strategies depend on the corporate financial performance, and patent publications are associated with the cost of applying for patents, the running costs of experimental materials, and the costs of the salaries of researchers. Thus, companies experiencing financial difficulties, especially due to the Asian financial crisis in 1997, decided to allocate their research and development resources toward profitable intellectual property rights in the short term to reduce their bankruptcy risk.

<Figure 1 about here>

Notably, the green patent share increased even though GDP growth decreased from 2007 to 2015. One interpretation of these different trends is that the social and market demands for environmental conservation increased due to worsening environmental problems, such as water and air pollution (Huang et.al., 2017; Fujii and Managi, 2017). The market demand for environmental protection increased the incentive for research and development activities focused on green technology because the expected profit from green patent inventions increased. In response to the market and social demands for environmental protection, the Chinese government enforced environmental policies and developed subsidies to promote green technology inventions.

Table 1 summarizes the Chinese policies related to environmental protection in each five-year plan. Pollution control requirements due to emission standards were established in the 9th and 10th five-year plans. Additionally, several policies related to energy conservation and cleaner production were enforced. In the period of the 11th five-year plan, which focused on creating a "harmonious society", the diffusion of renewable energy and a circular economy were promoted by the Chinese government to achieve sustainable development. Furthermore, an environmental information disclosure system was implemented in this period to make companies more environmentally friendly through stock market mechanisms (Fujii et al., 2011).

In 12th five-year plan period, the Chinese government strongly promoted pollution control to improve air and water pollution problems. Specifically, the Chinese government allotted 9.4 trillion yuan (1.37 trillion U.S.$) to fight water and air pollution (Chinadaily, 2015). These policy trends are reflected in the increasing number of green patent publications. As shown in Figure 1, the number of patent publications for waste management, including pollution control technologies, increased in the 12th five-year plan period.

<Table 1 about here>

During the 11th and 12th five-year plan periods, the Chinese economy slowly transitioned toward a harmonized economy. This study seeks to determine how research and development activities for green technology were different between the rapid economic development period (i.e., 9th and 10th five-year plans) and the gradual economic development period (i.e., 11th and 12th five-year plans). To address this research question, this study attempts to clarify the determinants of Chinese green patents from 1996 to 2015, with a focus on the differences in green technology development priorities in each five-year plan period. Figure 2 shows the research framework of this study. Factor decomposition analysis is applied to evaluate the key drivers of changes in green patent publications.

To define green technology, this study applies the definition introduced by the Organization for Economic Co-operation and development (OECD, 2009). To consider the characteristics of each green technology, we divided the data into four green patent groups based on the WIPO scheme: (1) alternative energy production, (2) energy conservation, (3) waste management, and (4) other green technology. A detailed explanation of this scheme is provided in section 3.

<Figure 2 about here>

2. Methodology

2-1. Patent decomposition analysis

We apply a decomposition analysis framework to clarify the influential factors associated with green patent publications. We use the following five indicators to decompose green patent inventions: the priority of a specific green technology (PRIORITY), the importance of green technology among all patent publications (GREEN), the efficiency of patent invention relative to R&D expenditure (EFFICIENCY), the share of R&D expenditure relative to the GDP (R&DSHARE), and the scale of economic activity (SCALE).

We define the PRIORITY indicator as the number of specific green patent publications divided by the total number of green patent publications, thus providing the share of specific green patent publications among all green patents. This indicator increases if the number of specific green patent publications increases more quickly than the total number of green patent publications, which indicates that inventors are concentrating their research resources on specific types of green technology inventions.

Similarly, the GREEN indicator is defined as the total number of green patent publications divided by the total number of patent publications, which indicates the share of total green patents out of all patents. This indicator increases if the number of total green patent publications increases more quickly than the number of total patent publications, which indicates that inventors are concentrating their research resources on specific green technology inventions.

EFFICIENCY indicates the efficiency of patent publication based on R&D expenditures. During the R&D process, expenditures are considered the input, and the number of patents is treated as the output. Thus, the number of patents produced by R&D expenditures reflects the efficiency of expenditures. This study tries to capture the efficiency of R&D expenditures using the EFFICIENCY indicator.

Next, the R&DSHARE indicator is defined as the R&D expenditure divided by the GDP, thus providing the ratio of R&D expenditure relative to the GDP. This indicator increases if the R&D expenditure increases more quickly than the Chinese GDP, which indicates that the government and companies are concentrating their economic resources on R&D activities.

Finally, the SCALE indicator is defined as the GDP and thus represents the scale of national economic activity. Generally, economic activity is related to R&D activity. For example, R&D expenditures declined after the financial crisis caused by the collapse of Lehman Brothers (Fujii et al., 2016). In this crisis, companies facing serious financial difficulties decided to scale down their R&D activities to decrease their bankruptcy risk. This scale down of R&D activities caused a decrease in the number of new patents publication, including those related to green patent technologies. Therefore, the scale of economic activity is an important factor for understanding why the number of green patent publications has changed.

Here, we introduce a decomposition approach using the pollution abatement technology group as a specific type of green patent publication (Table 1). The number of waste management technology patent publications (WASTE) is decomposed using the total number of green patents publication ($\mathrm{PATENT_{GREEN}}$), total number of patents publication (TOTAL), R&D expenditure (R&D), and economic activity (GDP), as shown in equation (1).

$$\begin{aligned}\mathrm{WASTE} &= \frac{\mathrm{WASTE}}{\mathrm{PATENT_{GREEN}}} \times \frac{\mathrm{PATENT_{GREEN}}}{\mathrm{TOTAL}} \times \frac{\mathrm{TOTAL}}{\mathrm{R\&D}} \times \frac{\mathrm{R\&D}}{\mathrm{GDP}} \times \mathrm{GDP} \\ &= \mathrm{PRIORITY} \times \mathrm{GREEN} \times \mathrm{EFFICIENCY} \times \mathrm{R\&DSHARE} \times \mathrm{SCALE}\end{aligned} \quad (1)$$

We consider the change in waste management technology patent publications from year t (WASTE^{t}) to year t+1 (WASTE^{t+1}). Using equation (1), the change in waste management technology patent publications can be represented as follows.

$$\frac{\mathrm{WASTE}^{t+1}}{\mathrm{WASTE}^{t}} = \frac{\mathrm{PRIORITY}^{t+1}}{\mathrm{PRIORITY}^{t}} \times \frac{\mathrm{GREEN}^{t+1}}{\mathrm{GREEN}^{t}} \times \frac{\mathrm{EFFICIENCY}^{t+1}}{\mathrm{EFFICIENCY}^{t}} \times \frac{\mathrm{R\&DSHARE}^{t+1}}{\mathrm{R\&DSHARE}^{t}} \times \frac{\mathrm{SCALE}^{t}}{\mathrm{SCALE}^{t-1}} \quad (2)$$

We can transform equation (2) into a natural logarithmic function and thus obtain equation (3).

$$\begin{aligned}&\ln(\mathrm{WASTE}^{t+1}) - \ln(\mathrm{WASTE}^{t}) \\ &= \ln\left(\frac{\mathrm{PRIORITY}^{t+1}}{\mathrm{PRIORITY}^{t}}\right) + \ln\left(\frac{\mathrm{GREEN}^{t+1}}{\mathrm{GREEN}^{t}}\right) + \ln\left(\frac{\mathrm{EFFICIENCY}^{t+1}}{\mathrm{EFFICIENCY}^{t}}\right) + \ln\left(\frac{\mathrm{R\&DSHARE}^{t+1}}{\mathrm{R\&DSHARE}^{t}}\right) + \ln\left(\frac{\mathrm{SCALE}^{t+1}}{\mathrm{SCALE}^{t}}\right)\end{aligned} \quad (3)$$

Multiplying both sides of equation (3) by $\omega_t^{t+1} = (\mathrm{WASTE}^{t+1} - \mathrm{WASTE}^{t})/\{\ln(\mathrm{WASTE}^{t+1}) - \ln(\mathrm{WASTE}^{t})\}$ yields equation (4) as follows.

$$\begin{aligned}&\mathrm{WASTE}^{t+1} - \mathrm{WASTE}^{t} = \varDelta\mathrm{WASTE}^{t,t+1} \\ &= \omega_t^{t+1}\ln\left(\frac{\mathrm{PRIORITY}^{t+1}}{\mathrm{PRIORITY}^{t}}\right) + \omega_t^{t+1}\ln\left(\frac{\mathrm{GREEN}^{t+1}}{\mathrm{GREEN}^{t}}\right) + \omega_t^{t+1}\ln\left(\frac{\mathrm{EFFICIENY}^{t+1}}{\mathrm{EFFICIENCY}^{t}}\right) \\ &+ \omega_t^{t+1}\ln\left(\frac{\mathrm{R\&DSHARE}^{t+1}}{\mathrm{R\&DSHARE}^{t}}\right) + \omega_t^{t+1}\ln\left(\frac{\mathrm{SCALE}^{t+1}}{\mathrm{SCALE}^{t}}\right)\end{aligned} \quad (4)$$

Therefore, changes in the number of patent publications for waste management technologies (⊿WASTE) are decomposed based on changes in PRIORITY (first term), GREEN (second term), EFFICIENCY (third term), R&DSHARE (fourth term), and SCALE (fifth term). The term ω_t^{t+1} operates as an additive weight to estimate the number of patents published for waste management technologies. This decomposition technique was developed by Ang et al. (1998) and is termed the logarithmic mean Divisia index (LMDI).

The LMDI approach is widely applied in energy and environmental science to address issues such as climate change (Chapman et al., 2018), energy security (Wang et al., 2018), and toxic chemical management (Fujii and Managi, 2013; Koh et al., 2016). Decomposition analysis using patent data is also widely applied in CO_2 reduction technology (Cho and Sohn, 2018), green chemical technology (Fujii, 2016), and artificial intelligence technologies (Fujii and Managi, 2018).

3. Data

We used patent publication data from the PATENTSCOPE database, which is provided by the World Intellectual Property Organization (WIPO). The PATENTSCOPE database provides information for more than 56 million patents. We specified green patents based on the green inventory patent classification scheme published by the WIPO (Table 2). We collected the patent-publication data on 7 February 2017 from the PATENTSCOPE database. As explained in Table 2, this study focuses on four green technology types: (1) waste management (WASTE), (2) alternative energy production (RENEWABLE), (3) energy conservation (CONSERVATION), and (4) other green technology (OTHER). Following Fujii (2016), we use only the primary IPC code and the primary applicant name to construct the patent data set and avoid double counting patent data.

<Table 2 about here>

Table 3 shows the average change in green patent publications by type of technology and the other variables that were included in the decomposition analysis. Notably, the average number of total patent publications in China dramatically increased from 488,849 in 2006-2010 to 1,271,679 in 2011-2015. According to Dang and Motohashi (2015), Chinese patent application law was revised in 2001 and 2009, which simplified patent applications for domestic firms. Additionally, Hu et al. (2017) pointed that a rapid increase of patent application at the State Intellectual Property Office of the People's Republic of China (SIPO) was caused by a new subsidy system and the revision of the patent law, and not by internal factors such as human resources for R&D and R&D priority changes. Thus, the revision of patent application law and new subsidy system promote to expand the R&D activities (e.g., patent invention) at the SIPO, which increased the number of green patent publications.

<Table 3 about here>

4. Results

Figure 3 shows the cumulative changes in green patent publications calculated using the LMDI model. Notably, the values in Figure 3 are based on the 1996 baseline. The plotted line shows the estimated cumulative patent publication change compared with the 1996 baseline, and the bar chart shows the cumulative effects of each determinant on patent publications. The sum of the bars is equivalent to the line.

<Figure 3 about here>

As shown in Figure 3, all four green patent publications increased due to the increases in the efficiency of patent invention, growth of R&D expenditures in the GDP, scale expansion of economic activities, and importance of green patents. Specifically, the efficiency of patent invention strongly contributed to the increase in green patent publications.

Moreover, the PRIORITY indicator contributed differently to patent publications by type of green technology. As shown in Figure 3(a) and 3(d), the PRIORITY indicator contributed to increases in the number of green patent publications related to waste management and other green technologies in recent years. However, the PRIORITY indicator negatively affected green patent publications related to renewable energy technology after 2011. This result implies that the priority of green patent invention shifted from renewable energy technology to waste management and other green technology in the period of the 12th five-year plan.

It should be noted that the bar chart reflects the scale of patent publication, which is represented as a line chart. The line chart rapidly increased beginning in the late 2000s. However, it is difficult to understand how the PRIORITY indicator changed in the 1990s and early 2000s because the patent publication scale is relatively small. To understand the PRIORITY indicator change in each five-year plan period, we estimate the ratio change of the PRIORITY indicator in each five-year plan. We introduce this value based on the waste management technology in the 9th five-year plan period. In this case, the ratio of change can be calculated as "the change in the PRIORITY indicator related to waste management from 1996 to 2000 divided by the number of patent publications related to waste management in 1996". Thus, the ratio represents how the PRIORITY indicator contributes to changes in specific green patent publications relative to those in the baseline year (first year of each five-year plan).

Figure 4 shows the change in the PRIORITY indicator for four specific green patent publications in China. As shown in Figure 4, the ratio of change of the PRIORITY indicator exhibited different trends among the five-year plans. For the 9th five-year plan, the PRIORITY indicators of waste management, renewable energy, and energy conservation technology contributed to increases in the number of patent publications. One interpretation of these results is that the market demand for these three technologies increased. In this period, an energy conservation law was enforced to promote technological development and diffusion for energy efficiency improvements. Additionally, emissions standard policies were implemented to reduce pollutant emissions from industrial sectors. Thus, industrial companies implemented energy conservation and waste management technologies to comply with environmental laws, which increased the incentive to develop technologies related to energy conservation and pollution control.

Another important point is that many developed countries tried to establish renewable energy systems and achieve the carbon reduction target of the Kyoto protocol adopted in 1997. This international policy provided a strong incentive for Chinese companies to develop renewable energy technology and increase their international market competitiveness in the renewable energy market.

In the period of the 10th five-year plan, the ratio of change was larger than that in the 9th five-year plan period. Additionally, the PRIORITY indicator of waste management contributed to a decrease in patent publications. This is an unexpected result because the PRIORITY indicator is significantly positive in the 9th five-year period, and several emission standards were also enforced in the 10th five-year plan period. As shown in Figure 4, the priority of research and development shifted from waste management to energy conservation in this period. One potential influence on these results was that of the energy price, which dramatically increased in the 2000s (Burke and Liao, 2015). This rapid energy price increase provided a strong incentive for technological development for energy conservation.

Next, we discuss the ratio of change of the PRIORITY indicator in the period of gradual economic development. In the period of the 11th five-year plan, the ratio of change of the PRIORITY indicator was very low compared with those in the other five-year periods. This result implies that the research and development strategies for all the green technologies were similar in the period of the 11th five-year plan. It should be noted that the share of green patent publications in total patent publications increased in this period (see Figure 3). Thus, environmental policies in China promoted the research and development of overall green technology in the 11th five-year plan period.

In the period of the 12th five-year plan, the ratio of change of the PRIORITY indicator related to waste management and other green technology contributed to an increase patent publications. Notably, other green technology includes general green vehicles, which can greatly reduced air pollution from the transportation sector. One interpretation of these results is that serious air pollution exists in urban areas in China. Serious urban air pollution affects human health, and people complain about urban air quality (Huang et al., 2017). In the 12th five-year plan, people in urban areas achieved economic development and became health conscious. In this context, the government promoted research and development activities involving air pollutant abatement technologies in the industrial sector and exhaust emission controls for automobiles. In addition to air pollutant problems, the Chinese government allocated a large budget for water quality improvements (Fujii and Managi, 2017). These allocations increased the incentive to develop water pollution abatement technologies for future environmental markets based on expanded governmental budgets.

Another important finding is that the ratio of change of the PRIORITY indicator related to renewable energy technology decreased in the 12th five-year plan period. This result can be explained by the status of the international renewable energy market. Many countries established a feed-in tariff as a subsidy to diffuse renewable energy systems, especially solar photovoltaics. Moreover, the subsidy system failed in several countries (e.g., the feed-in tariff policy in Spain), and the international market demand shrunk (Ibarloza et al., 2018). As a result, the excess stock of solar photovoltaic products increased and the product price decreased, which decreased the profit margin. In this scenario, the incentive for the technological development of solar photovoltaic technologies decreased in the period of the 12th five-year plan in China.

<Figure 4 about here>

5. Conclusion

This study investigated the factors that contributed to green patent publications change in China from 1996 to 2015 using decomposition analysis. We focused on four green technologies: waste management, alternative energy technology, energy conservation, and other green technologies. The key results are summarized as follows.

First, the number of patent applications related to green patent publications increased due to increases in the efficiency of the patent invention process, the importance of green technology, the proportion of research and development expenditure in the GDP, and the scale expansion of economic activities.

Second, the number of green patent publications related to waste management and other green technologies increased due to the research prioritization in the 12th five-year period and the relative priority decline in renewable technology. This finding implies that the relative priority of green technology development shifted from renewable energy to waste management and other green technology.

Finally, we observed that the priority changes in green technology invention were diverse among the five-year plans. The differences in green technology characteristics are useful for understanding domestic and international market demands and high priority technology types and for developing strategies to achieve green growth in China.

Implications for emerging countries is identified through this study. From the above findings, we can better understand the research priority of sustainable green technological invention in China. Changes in research priorities are key factors in enhancing private companies to promote new technology inventions. Governments in emerging countries design their policies and subsidies to enhance private companies to invent sustainable green technologies to achieve the balance between environmental conservation and economic development. Meanwhile, emerging countries need to spend a lot of budget for infrastructure building and human resource development, and available budget for research and development is limited. To evaluate the cost-effectiveness of these governmental policies, identification of major driver for technological invention is key information for policy maker. Thus, we believe the proposed decomposition research framework is a useful tool to establish a strategic plan for sustainable technology invention considering both research priority change, efficiency of budget allocation, and scale of research and development activities.

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Table 1. Environmental policies in China

Period	Environmental policy
9th Five-Year Plan (1996-2000)	-Integrated emissions standard for air pollutants (1997) -Emissions standard for air pollutants from industrial kilns and furnaces (1997) -Emissions standard for air pollutants from coke ovens (1997) -Energy conservation law (1998) -State council approves plotting programs for acid rain control and SO_2 control regions (enacted in 1998, implemented in 2002)
10th Five-Year Plan (2001-2005)	-Emissions standard for air pollutants from coal-burning, oil-burning, and gas-fired boilers (2001) -Technology policies for SO_2 emission control from coal combustion (2002) -Law on the promotion of cleaner production (2003) -State council issues regulations on pollution (2003) -Emissions standard for air pollutants from the cement industry (2004)
11th Five-Year Plan (2006-2010)	-Renewable energy law (2006) -Comprehensive working plan for energy conservation and emission reductions (2007) -State Environmental Protection Administration was upgraded to the Ministry of Environmental Protection in China (2008) -Measures for open environmental information (2008) -Circular economy promotion law (2008)
12th Five-Year Plan (2011-2015)	-Twelfth Five-Year Plan set key themes that included rebalancing the economy, ameliorating social inequality and protecting the environment (2011) -Ambient air quality standard (enacted in 2012, implemented in 2016) -Water Pollution Prevention and Control Action Plan (Water Ten Plan) (2015) -New environmental protection law was enforced (2015)

Table 2. Descriptions of the green patent groups

Technology group (code)	Technology subgroup
Waste management (WASTE)	(1) Waste disposal, (2) Treatment of waste, (3) Consuming waste by combustion, (4) Reuse of waste materials, (5) Pollution control
Alternative energy production (RENEWABLE)	(1) Biofuels, (2) Integrated gasification combined-cycle fuel cells, (3) Pyrolysis or gasification of biomass, (4) Harnessing energy from manmade waste, (5) Hydroenergy, (6) Ocean thermal energy conversion, (7) Wind energy, (8) Solar energy, (9) Geothermal energy, (10) Other production or use of heat not derived from combustion, (11) Using waste heat, (12) Devices for producing mechanical power from muscle energy
Energy conservation (CONSERVATION)	(1) Storage of electrical energy, (2) Power supply circuitry, (3) Measurement of electricity consumption, (4) Storage of thermal energy, (5) Low-energy lighting, (6) Thermal building insulation, in general, (7) Recovering mechanical energy
Other green technology (OTHER)	(1) Vehicles, in general, (2) Vehicles other than rail vehicles, (3) Rail vehicles, (4) Marine vessel propulsion, (5) Cosmonautic vehicles using solar energy, (6) Forestry techniques, (7) Alternative irrigation techniques, (8) Pesticide alternatives, (9) Soil improvement, (10) Commuting, (11) Carbon/emissions trading, (12) Static structure design, (13) Nuclear engineering, (14) Gas turbine power plants using heat sources of nuclear origin

Source: IPC green inventory of the WIPO (http://www.wipo.int/classifications/ipc/en/est)

Table 3. Green patent publication data and other variables included in the decomposition analysis

Data variable	Unit	1996-2015	1996-2000	2001-2005	2006-2010	2011-2015
Green patents	Item	39,398	4,122	10,450	34,512	108,507
Waste	Item	13,411	1,512	4,293	13,416	34,421
Renewable	Item	9,786	1,249	2,734	7,774	27,387
Conservation	Item	8,976	653	2,006	7,324	25,922
Other	Item	7,225	708	1,417	5,998	20,776
Total patents	Item	507,386	80,747	188,270	488,849	1,271,679
R&D expenditures	Million Yuan	499,120	187,319	334,850	513,289	903,477
GDP	Billion Yuan	3,510	2,709	2,950	3,754	4,629

Note: Each number is the average value in each period. Monetary data are deflated based on the 2010 price.

Source: Authors' estimation using the PATENTSCOPE database and the IPC code listed "IPC Green Inventory" provided by WIPO (http://www.wipo.int/classifications/ipc/en/green_inventory/).

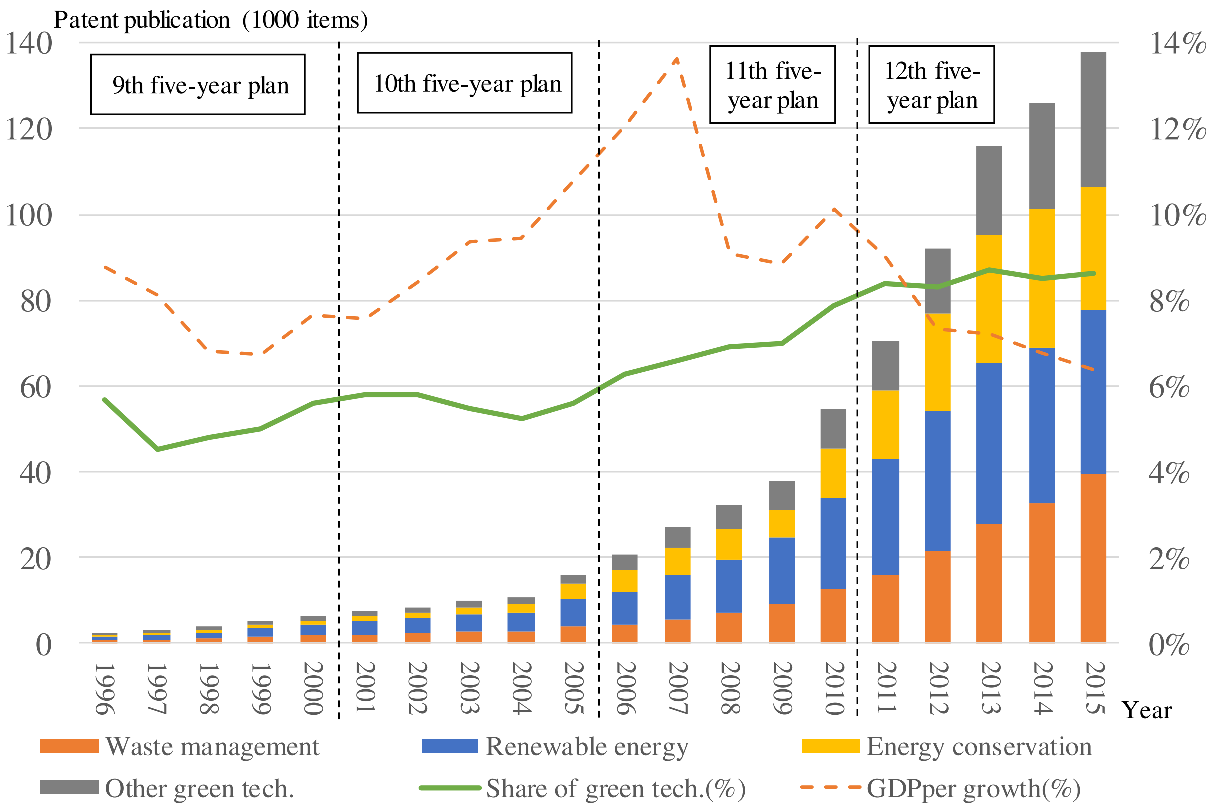

Figure 1. Trends of green sustainable technology invention in China

Source: PATENTSCOPE database from the WIPO and the World Development Indicator from the World Bank

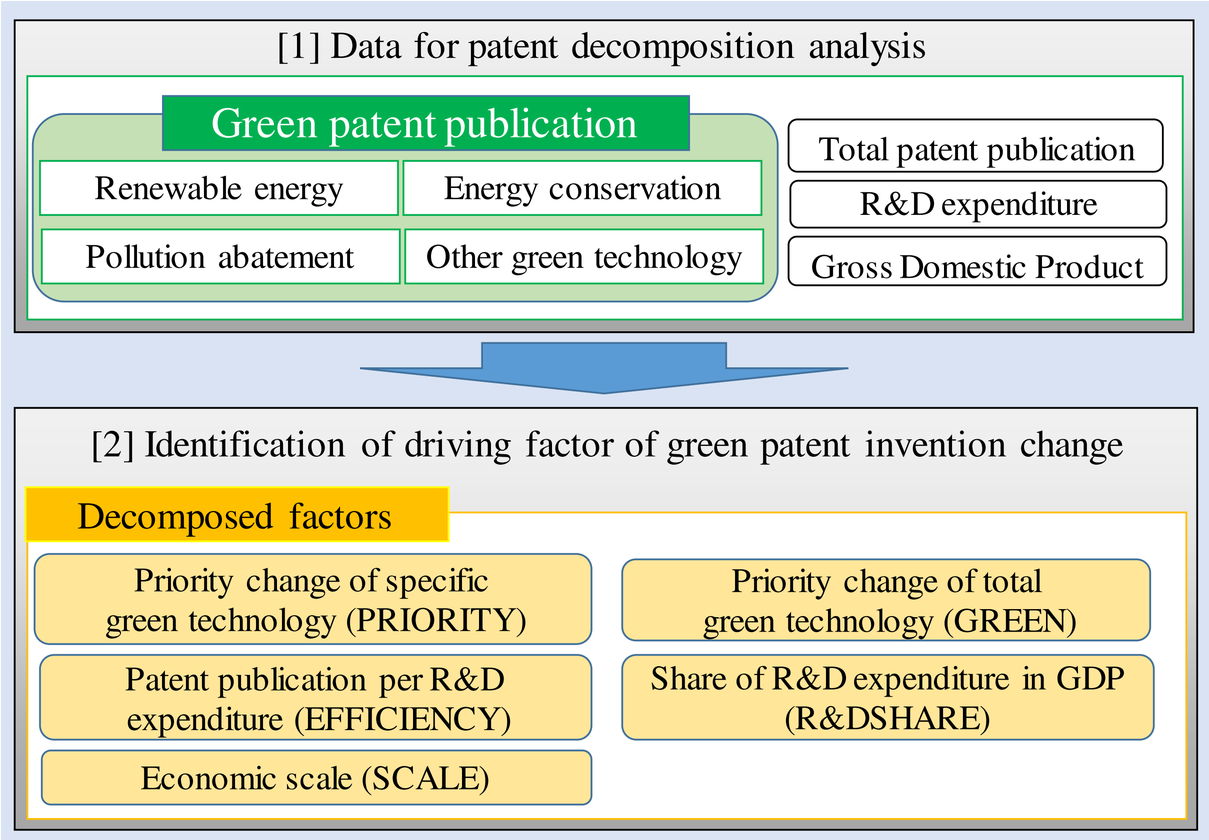

Figure 2. Research framework of this study

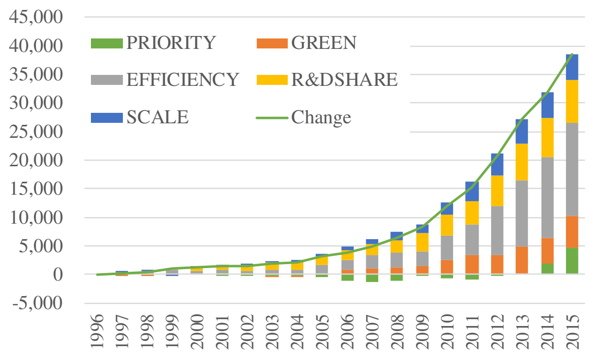

Figure 3(a) Waste management technology

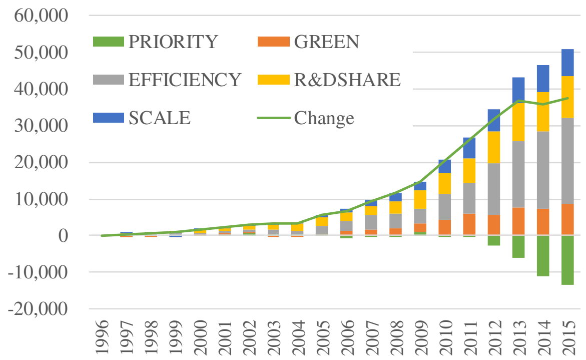

Figure 3(b) Renewable energy technology

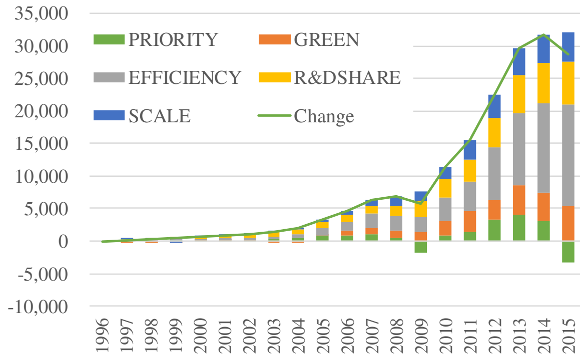

Figure 3(c) Energy conservation technology

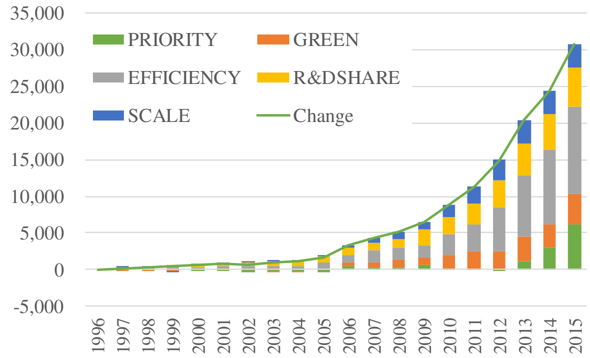

Figure 3(d) Other green technology

Figure 3. Results of patent decomposition analysis by type of green technology

Note: the vertical axis represents the number of patent publications for each specific green technology

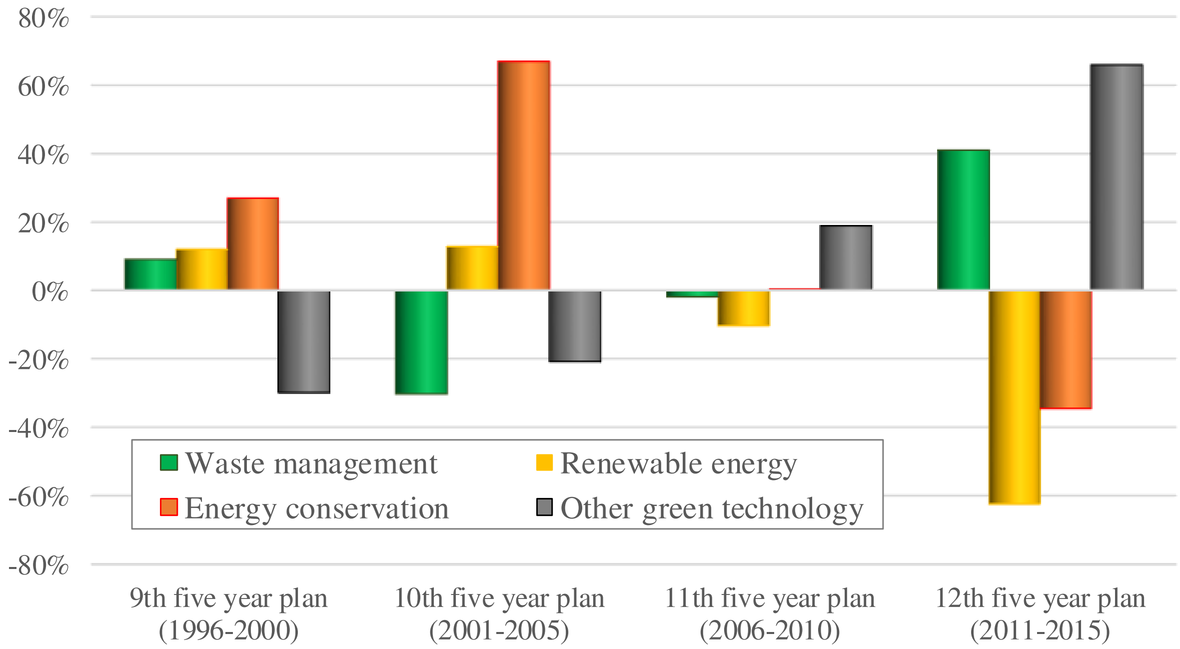

Figure 4. Comparative analysis of priority indicators in each period by type of green technology