https://doi.org/10.1016/j.techfore.2016.02.012

Research and development strategy for environmental technology in Japan: A comparative study of the private and public sectors

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Abstract: Environmental protection technology plays an important role in a sustainable society, simultaneously promoting economic development and pollution control. This study examines the determinants of technology inventions related to environmental protection in Japan. We use patent application data in a decomposition analysis framework. We find that environmental patent applications increase according to the prioritization of environmental patents by private companies and according to efficiency improvements in patent applications in the public sector. Additionally, patent applications related to emissions trading increased rapidly among private companies, mainly due to their increased priority after 2005. The different determinants of environmental technologies between the private and public sectors are useful for formulating effective policies to promote environmental innovation.

Keywords: *Green invention, decomposition analysis, research and development strategy, patent data, log mean Divisia index*

1. Introduction

Environmental protection technology (hereafter, environmental technology) plays an important role in effectively and economically controlling pollutant emissions. In this way, such technology contributes to the creation of a sustainable society, that is, one balancing economic development and environmental protection (Sun et al., 2008). The global importance of environmental technology has been increasing. Environmental technology is listed as a high priority in Japan's 5th science and technology basic plan, which covers 2016 to 2020. Similarly, the U.S. government budgeted approximately 7.4 billion U.S. dollars for clean energy technology programs in 2016. Additionally, Germany's high-tech innovation strategy, introduced in 2014, includes creating a sustainable economy and energy supply as one of its six priority tasks. These research and development strategies focus on the expansion of the environmental business market and are intended to improve international market competitiveness.

However, not all environmental technologies contribute equally to improved pollution control and resource conservation. Technology for environmental protection is diverse and comes in many forms. Some of these are pollution control technologies applicable to waste management, air pollution control, and wastewater treatment. The resource conservation area includes renewable energy, energy efficiency improvements, and energy-saving products. It is clear that the market demand for and cost of inventions differ depending on the type of environmental technology. Therefore, it is important to consider the characteristics of each environmental technology when suggesting an economical and effective environmental technology invention system. To understand the characteristics of environmental technologies, clarification is imperative.

The clarification of environmental technology was introduced by the Organization for Economic Co-operation and Development (OECD, 2009) and the World Intellectual Property Organization (WIPO, see http://www.wipo.int/classifications/ipc/en/est/). Meanwhile, previous literature focusing on the characteristics of environmental technology patents (hereafter, environmental patents) is limited, and most studies focus on the U.S. and European countries (Fujii, 2016). In recent years, several academic studies have focused on specific environmental technologies, such as wind energy technology in Europe (Lindman and Söderholm, 2015) and green chemistry in Japan (Fujii, 2016).

Fujii (2016) applied a factor decomposition analysis to identify the determinants of patent applications related to green chemistry in Japan. This study addressed green chemistry but not other environmental technologies. Therefore, pollution control and alternative energy technologies, which have different characteristics from green chemistry, are not discussed in Fujii (2016). Additionally, few previous studies have used Japanese environmental patent data. Therefore, there is no previous research providing a factor decomposition analysis of the determinants of environmental patents in Japan that focuses on the characteristics of each technology. However, the results of such a factor analysis, which considers the characteristics of specific environmental technologies, are important for creating effective research and development policy.

This study tries to clarify the determinants of Japanese environmental patents from 2001 to 2010. During this period, the so-called "lost decades," the Japanese economy experienced slow growth due to high appreciation of the yen and reduced consumer spending in the domestic market (Hamada and Okada, 2009; Lise et al., 2014). Studies of how research and development advanced in Japan during the lost decades are limited, especially concerning environmental technologies. However, according to the OECD (2014), Japan led the world in high-value inventions in environmental technology between 2009 and 2011. This pattern shows that Japan was highly competitive in research and development technology in 2011. Interestingly, Japan invented environmental technologies during an economic depression, during which reductions in R&D expenditures would normally be expected.

Figure 1 presents the number and share of patent applications for environmental technologies from 1990 to 2010. The bars illustrate the number of patent applications for environmental technologies by type of technology, following the WIPO environmental patent classification. Figure 1 also shows the GDP growth rate. During the 1990s and 2000s, the GDP growth rate in Japan stagnated around 0%; it dramatically declined in 1998 and 2009 due to the Asian financial crisis in 1997 and the global financial crisis triggered by the collapse of Lehman Brothers in 2008, respectively. Figure 1 shows that the share of environmental patent applications, out of total patent applications, gradually increased from 3% to 9% over the 1990-2010 period. One interpretation of this change is that market and social demand for environmental protection were increased by worsening environmental problems, such as climate change (Jin, 2015).

<Figure 1 is here>

Table 1 summarizes both Japanese policies and international events related to environmental technology invention. Table 1 lists pollution control policies focusing on the early 1990s. Environmental management and climate change mitigation were required beginning in the late 1990s. Since 2000, both climate change mitigation and appropriate handling of toxic chemical substances have been subject to strong international demand (Ermoliev et al., 2015). These policy trends are reflected in increasing environmental patent application shares. As seen in Figure 1, the number of patent applications for waste management, including pollution control technologies, increased during the early 1990s. Since the late 1990s, energy conservation and alternative energy production have increased each year. In addition, the administrative, regulatory, and design aspects of technology, including emissions trading technologies, increased dramatically after the Kyoto Protocol, which entered into force in 2005.

<Table 1 is here>

As mentioned above, decision making for research and development strategy differs by the type of environmental technology because of differences in the costs, expected profits, and market competitiveness of each technology.[1] Additionally, R&D strategies for environmental technology differ between private companies and the public sector. Table 2 shows the breakdown of private and public sector R&D expenditures and numbers of patent applications. Most patent applications were filed by private companies. However, the public sector did increase its patent applications gradually from 2000 to 2010.

[1] Some companies employ corporate strategies focusing on their secret core technology and know-how. Fujii et al. (2015) focus on the relation between corporate productivity changes and corporate R&D strategies using productivity analysis and questionnaire data. They concluded that companies employing confidential information systems tend to increase their productivity. Meanwhile, confidential corporate information about R&D strategy is difficult to collect for manufacturing firms. Thus, analysis of the confidential information strategy effect is not a main focus of this study.

In the private sector, most R&D spending is for technology and product development, while in the public sector, approximately 75% of spending is for basic and applied research. It is clear that private companies focus on development because they face the threat of bankruptcy if their products lose competitiveness in the market. Thus, private companies concentrate their R&D resources on product development because this directly contributes to corporate profits over the short term. Additionally, the R&D expenditures of private companies are financed by corporate profits. According to the 2014 Survey of Research and Development in Japan, 91% of R&D expenditures in private companies come from self-financed budgets. Meanwhile, 97% of R&D expenditures in the public sector come from central and local government budgets. This is one reason for the low share of R&D expenditures allocated to basic research, which contributes to corporate profits only over the long term. In other words, investing profits in basic research technology is quite risky for private firms. Recently, several types of fund raising instruments have been applied by private companies in Japan. For example, the Toyota Motor Corporation (TMC) created a unique fundraising system to support its R&D activities.[2]

On the contrary, the R&D expenditures of public research institutes are mainly financed by government budget allocations. Much of the research budget from the government is directed toward increasing the international technological competitiveness of Japanese basic research or applied research over the long term, thus promoting social welfare rather than short-term profits. Therefore, R&D strategies differ between the private and public sectors because of differences in the objectives and financing of R&D activities.

<Table 2 is here>

[2] According to TOYOTA Motor Corporation (2015), "Toyota Motor Corporation ("TMC") announced today the pricing of a public offering in Japan of 47,100,000 new shares of First Series Model AA Class Shares of TMC (the "Model AA Class Shares"), at the offer price of 10,598 yen per share. TMC expects to receive net proceeds of approximately 475.0 billion yen from the offering. TMC intends to use the proceeds for research and development of next-generation innovation, including the development of fuel battery vehicles, research on infrastructure and development of computerized and sophisticated intelligence mobility technology."

As discussed above, many previous studies have focused on environmental technologies. However, most of them analyzed patent data for Europe and the U.S.; few studies have used Japanese patent data. Additionally, most previous studies have not discussed the characteristics of the inventors, even though R&D strategies clearly differ in the private and public sectors. Based on this background, the objective of this study is to clarify the determinants of environmental patents among Japanese manufacturing firms and public sector actors. To consider the characteristics of each environmental technology, we divided the data into seven environmental patent groups, following the WIPO[3]: (1) alternative energy production, (2) transportation, (3) energy conservation, (4) waste management, (5) agriculture/forestry, (6) administrative, regulatory or design aspects, and (7) nuclear power generation. This study analyzes why the share of Japanese environmental patent applications increased during Japan's lost decades by focusing on the R&D strategies of private companies and public research institutes and considering the characteristics of each environmental technology.

The remainder of this paper is organized as follows. Section 2 describes the decomposition analysis methodology. Section 3 describes the dataset. The results of the decomposition analysis using Japanese environmental patent data are discussed in Section 4, and Section 5 concludes.

2. Methodology

We apply a decomposition analysis framework to identify the factors driving environmental patent applications in Japan. To decompose patent applications related to environmental technology, we use four indicators: [1] the priority of a specific environmental technology (PRIORITY), [2] the share of all patent applications focusing on environmental technology (ENVSHARE), [3] the efficiency of R&D expenditures in patents (EFFICIENCY), and [4] the scale of R&D activities (SCALE).

[3] The WIPO environmental patent classification is popular in patent data analysis. For example, Albino et al. (2014) applied it to identify patents related to low-carbon energy technology. They use 131,661 patent items for low-carbon energy technology from 1971 to 2010 in the U.S. Durán-Romero and Urraca-Ruiz (2015) examined 50,087 patent data items related to climate change mitigation from 1978 to 2010 in Europe using the WIPO patent classification.

We define the PRIORITY indicator as the number of specific environmental technology patent applications divided by the total number of environmental patent applications, yielding the share of patent applications for specific technologies. The value of the indicator increases if the number of specific environmental technology patent applications increases more rapidly than the total number of environmental patent applications, thus indicating that inventors have concentrated their research resources on a specific environmental technology. We can infer that inventors assign higher priority to specific environmental technologies over other types of environmental technologies if PRIORITY increases.[4]

Similarly, the ENVSHARE indicator is defined as the total number of environmental patent applications divided by total number of patent applications, yielding the share of total environmental patent applications. The value of this indicator increases if the number of total environmental patent applications increases more rapidly than the number of total patent applications, thus indicating that inventors have concentrated their research resources on environmental technologies. Inventors assign higher priority to inventing environmental technologies over other types if ENVSHARE increases.

EFFICIENCY indicates the efficiency of patent generation 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 the expenditures. This efficiency clearly differs by technological classification (e.g., technologies that require expensive materials for experiments yield few patents for a given amount of R&D spending). This study tries to capture the efficiency of R&D expenditures and the composition of patent technologies by EFFICIENCY.

Finally, the SCALE indicator is defined by R&D expenditures and thus represents the scale of R&D activities. Generally, the scale of R&D activities is strongly related to the number and budget of each research project. Thus, total R&D expenditures reflect the level of active R&D efforts.

[4] The number of patent applications for specific environmental technologies increases due to disruptive innovation. In this case, the PRIORITY indicator is also affected by the effect of disruptive innovation. Therefore, a dramatic change in the PRIORITY indicator implies either a corporate priority change due to disruptive innovation or a policy and market change (e.g. new subsidy system, new business market). Thus, we believe our research framework can identify the possibility of disruptive innovation by considering changes in the PRIORITY indicator.

Additionally, the R&D activities of companies strongly depend on the corporate financial situation because patent applications are associated with their R&D investment. For example, the number of patent applications declined after the global financial crisis triggered by the collapse of Lehman Brothers (OECD, 2009). Thus, companies facing financial difficulties reduced their R&D activities to reduce their bankruptcy risk. This decrease in R&D activities followed a decline in R&D expenditures. Therefore, the scale of R&D activity is an important factor explaining why the number of environmental patent applications changes. The value of SCALE can increase if R&D expenditures increase. The number of patent applications for a specific environmental technology increases with the scaling up of overall R&D activities reflected in an increase in SCALE.

Here, we introduce the decomposition approach using waste management patents as an example. The number of waste management patent applications (WASTE) is decomposed using total environmental patent applications (ENVIRONMENT), total patent applications (TOTAL), and R&D expenditures (R&D) in equation (1).

$$\mathrm{WASTE} = \frac{\mathrm{WASTE}}{\mathrm{ENVIRONMENTAL}} \times \frac{\mathrm{ENVIRONMENTAL}}{\mathrm{TOTAL}} \times \frac{\mathrm{TOTAL}}{\mathrm{R\&D}} \times \mathrm{R\&D}$$

$$= \mathrm{PRIORITY} \times \mathrm{ENVSHARE} \times \mathrm{EFFICIENCY} \times \mathrm{SCALE} \qquad (1)$$

We consider the change in waste management patent applications from year t-1 (WASTE^{t-1}) to year t (WASTE^{t}). Using equation (1), the growth ratio of waste management patent applications can be represented as follows:

$$\frac{\mathrm{WASTE}^{\mathrm{t}}}{\mathrm{WASTE}^{\mathrm{t-1}}} = \frac{\mathrm{PRIORITY}^{t}}{\mathrm{PRIORITY}^{t-1}} \times \frac{\mathrm{ENVSHARE}^{t}}{\mathrm{ENVSHARE}^{t-1}} \times \frac{\mathrm{EFFCIENCY}^{t}}{\mathrm{EFFCIENCY}^{t-1}} \times \frac{\mathrm{SCALE}^{t}}{\mathrm{SCALE}^{t-1}}$$

(2)

A natural logarithmic transformation of equation (2) yields equation (3)[5].

$$\ln\mathrm{WASTE}^{t} - \ln\mathrm{WASTE}^{t-1} = \ln\left(\frac{\mathrm{PRIORITY}^{t}}{\mathrm{PRIORITY}^{t-1}}\right) + \ln\left(\frac{\mathrm{ENVSHARE}^{t}}{\mathrm{ENVSHARE}^{t-1}}\right) + \ln\left(\frac{\mathrm{EFFICIENCY}^{t}}{\mathrm{FFCIENCY}^{t-1}}\right) + \ln\left(\frac{\mathrm{SCALE}^{t}}{\mathrm{SCALE}^{t-1}}\right)$$

(3)

Multiplying both sides of equation (3) by $\omega_i^t = (\mathrm{WASTE}^{t} - \mathrm{WASTE}^{t-1})/(\ln\mathrm{WASTE}^{t} - \ln\mathrm{WASTE}^{t-1})$ yields equation (4).[6]

$$\mathrm{WASTE}^{t} - \mathrm{WASTE}^{t-1} = \triangle\mathrm{WASTE}^{t,t-1}$$

$$= \omega_i^t \ln\left(\frac{\mathrm{PRIORITY}^{t}}{\mathrm{PRIORITY}^{t-1}}\right) + \omega_i^t \ln\left(\frac{\mathrm{ENVSHARE}^{t}}{\mathrm{ENVSHARE}^{t-1}}\right) + \omega_i^t \ln\left(\frac{\mathrm{EFFICIENCY}^{t}}{\mathrm{EFFICIENCY}^{t-1}}\right) + \omega_i^t \ln\left(\frac{\mathrm{SCALE}^{t}}{\mathrm{SCALE}^{t-1}}\right)$$

(4)

Therefore, changes in the number of patent applications in waste management ($\triangle$WASTE) are decomposed into changes in PRIORITY (first term), ENVSHARE (second term), EFFICIENCY (third term), and SCALE (fourth term). The term ω_i^t operates as an additive weight for the estimated number of patent applications for waste management technologies. This decomposition technique, the

[5] Zero values in the dataset cause problems in the decomposition because of the properties of logarithmic functions. To solve this problem, the LMDI literature suggests replacing the zero values with a small positive number (Ang and Liu, 2007).

[6] $\omega_i^t = 0$ if $\mathrm{WASTE}^{t} = \mathrm{WASTE}^{t-1}$ (Fujii et al., 2013)

logarithmic mean Divisia index (LMDI) approach, was developed by Ang et al. (1998). Ang (2004) noted that LMDI is the preferred method for decomposition analysis because of its theoretical foundation, adaptability, ease of use and results interpretation, and lack of the residual terms generated by Laspeyres-type methods. The LMDI approach is widely applied in environmental science to address issues such as climate change (de Freitas and Kaneko, 2011) and toxic chemical management (Fujii and Managi, 2013).

The novel contribution of this research is to clarify R&D strategies using LMDI analysis and patent application data. Many previous studies have focused only on the number of patent applications, which is affected by the priority, efficiency, and scale of R&D activities. Thus, this study clarifies the contributions of each determinant to changes in environmental patent applications using decomposition analysis. Fujii (2016) first applied a decomposition framework to patent data using two factors: priority and scale. In this study, we extend this approach to clarify the determinants of patent applications using four factors: 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.[7]

3. Data

We used patent application data from the database published by the Institute of Intellectual Property (IIP) (Goto and Motohashi, 2007). The IIP Patent database covers 12,706,640 patent applications filed from 1964 to 2012[8]. We specified the environmental technology patents following the green inventory patent classification published by the WIPO. As explained above, this study focuses on seven environmental technologies: (1) alternative energy production, (2) transportation, (3) energy conservation, (4) waste management, (5) agriculture/forestry, (6) administrative, regulatory or

[7] A limitation of our research framework is the difficulty of completely understanding the effects of policies and international events on patent invention activity. In order to completely understand the causal relationship between priority changes and policy, we would need to interview the corporate R&D managers of many companies. This approach requires substantial time and effort. In the meantime, our research framework has the advantage of being cost-effective, which means that corporate priority changes can be clarified by using a decomposition framework and published patent application data, which are freely available (e.g. IIP patent database).
[8] The patent database was constructed using standardized data from the Japan Patent Office through its 25th release.

design aspects, and (7) nuclear power generation. Table 3 provides detailed patent classification of green inventory technologies.

<Table 3 is here>

Additionally, we use R&D expenditure data from 2001 to 2010 for both the private and public sectors. The R&D expenditure dataset is obtained from the Survey of Research and Development published by the Statistics Bureau of Japan.[9] In this survey, R&D expenditure data are available for private companies, non-profit research institutes, and universities. R&D expenditures include research salaries, material costs for experiments, expenses for physical fixed assets, and lease fees. We combine the non-profit research institute and university data into public sector data. R&D expenditure data are deflated to 2010 prices using an R&D deflator that is available from the Indicators of Science and Technology published by Japan's Ministry of Education, Culture, Sports, Science and Technology. To maintain consistent data coverage for patent applications and R&D expenditures, we construct the patent application dataset for the private and public sectors following the grouping methodology applied in the Survey of Research and Development.

According to Fujii (2016), there are advantages and disadvantages to using patent data to analyze R&D strategies.[10] The disadvantage is the difficulty of evaluating the quality of patent applications. Generally, patent applications that are granted have higher private values than those that are withdrawn or refused. However, patent application data do not control for the quality of technologies. The patent-granted count method is mainly employed to examine the diffusion of technologies (e.g.,

[9] The sample coverage of the Survey of Research and Development is introduced by the Statistics Bureau of Japan as follows. "The survey covered approx. 13,400 business enterprises, approx. 1,100 non-profit institutions and public organizations, and approx. 3,700 universities and colleges, for a total of approx. 18,200. The response ratio was approx. 87%. (approx. 83% of the business enterprises, approx. 99% of the non-profit institutions and public organizations, and approx. 100% of the universities and colleges)". http://www.stat.go.jp/english/data/kagaku/1530.htm

[10] Another approach is using scientific publications to analyze R&D strategies and activities. However, it is difficult to use scientific publication data for this study because there is no detailed classification of environmental technologies in scientific publications. Therefore, a keyword search method must be employed to obtain the data. A keyword search method may include scientific journals that are not directly related to environmental technologies. Thus, obtaining scientific publication count data that correctly reflects inventors' R&D strategies is difficult.

Popp (2006)). However, patent-granted data do not include information about unsuccessful patent applications even though these reflect the R&D strategy.

Meanwhile, an advantage of patent application data is that they cover all R&D activities reflected in inventors' strategies (Fujii, 2016). In addition, an application fee is required to file the patent application. Thus, inventors are likely to be confident that their invention will pass the examination process if they submit a patent application. Therefore, we believe that patent application data are more accurate measures of inventors' R&D activities and strategies than are data on granted patents. Focusing on these points, Cavalheiro et al. (2014) and Fujii (2016) used patent application data to analyze R&D strategies. This study therefore uses patent application data to represent inventors' R&D strategies with respect to environmental technologies.

This study applied the International Patent Classification (IPC) green inventory classification introduced by the WIPO to divide each patent application into seven technology groups. Some patent applications are registered to multiple applicants. To avoid double counting patent application data, we use only the primary applicant's information to construct the dataset. Following this procedure, we construct an environmental patent application dataset by type of technology and inventor.

Table 4 shows the share of environmental patent applications by industry and sector. We apply the industrial classification approach introduced by the Japan Exchange Group.[11] We select four industries, which represents a large share of environmental patent applications. The public sector is divided into three organizations whose shares equal 100%. In table 4, government includes local governments and Japanese ministries. The trends in patent applications are reflected in the industry and public sectors' characteristics presented in table 4.

<Table 4 is here>

[11] The industrial classification for listed companies produced by the Japan Exchange Group is a popular approach. Most exchanges in Japan, including the Tokyo stock exchange and Osaka stock exchange, accept this approach.

The four industries in table 4 represent 57.5% of total environmental patent applications in Japan from 2001 to 2010. The electric products industry share is approximately 30%. The electric products industry also represents a large share of alternative energy production, energy conservation, and nuclear power generation, which are directly related to energy. Additionally, the electric products industry represents 34.6% of administrative, regulatory or design aspects of technology due to the increase in patent applications related to emissions trading technology after 2005.

Next, the transportation equipment industry represents more than 60% of environmental patent applications in the transportation technology field. Patent applications related to hybrid vehicles, fuel cell vehicles, and fuel economy performance improvements represent a large share of this group. The general machinery industry represents a relatively high share of the waste management technology group because a law concerning special measures against dioxins entered into force in Japan in 2000, spurring companies in the general machinery industry to invent new technologies for high temperature incineration plants. Finally, the chemical products industry's share of 23.9% of environmental patent applications is related to agriculture and forestry. Most applications are related to chemical fertilizers and antiseptic dusting powders, which increase agricultural productivity due to effective harvesting and forest resource management.

Next, we consider the public sector data. Table 4 indicates that public research institutes represented more than half of environmental patent applications filed by public sector actors. Specifically, public research institutes filed 87.3% of patent applications related to nuclear power generation, which requires specialized knowledge and safety equipment for experiments. Most nuclear power generation technologies are invented by the Japan Atomic Energy Agency, which has sufficient expert researchers and specialized equipment.

Surprisingly, the government filed 11.8% and 17.9% of patent applications related to waste management and agriculture/forest technologies, respectively. The majority of patent applications are for pollution control in waste management and for organic fertilizers derived from waste products and pesticide alternatives in agriculture and forest technology. The government invented these environmental technologies because in Japan, the management of garbage dumps, forest resources, and agricultural businesses is strongly dependent on local governments. Therefore, governmental staff have incentives to invent technologies to improve their management performance.

4. Results

Figures 2 and 3 and tables 5 and 6 show the accumulated changes in environmental patent applications calculated using the LMDI model. Figures 2 and 3 show the results of the decomposition analysis for total environmental patent applications by private companies and public sector actors from 2001 to 2010. The scores in figures 2 and 3 represent the accumulated changes in total environmental patent application ratios based on a 2001 baseline. To conduct the decomposition analysis for the change in total environmental patent applications, the priority term is dropped form the LMDI model.[12] The plotted line shows the estimated accumulated patent application change ratios, and the bar chart shows the accumulated effects of each determinant on patent applications. The sum of the bars is equivalent to the line.

Tables 5 and 6 show the results of the decomposition analysis for changes in environmental patent applications by type of technology from 2001 to 2010. In tables 5 and 6, positive scores indicate increases in patent applications, while negative scores imply patent application decreases from 2001 to 2010. Using the results presented in tables 5 and 6, a comparative analysis by type of technology is possible.

Here, we discuss the results for private companies, focusing on figure 2 and table 5. Figure 2 represents the increase in total environmental patent applications from 2002 to 2006 due to the increasing share of environmental patents relative to total patent applications and the scaling up of R&D activities. Meanwhile, the efficiency of patent applications contributed negatively to environmental patent application growth. We can provide two reasons for this negative effect of efficiency among private companies. First, technological inventions usually become more difficult

[12] To conduct a decomposition analysis for changes in total environmental technology patent applications, the left-hand side of equation (4) is $envshare^{t}$-$envshare^{t-1}$. In this case, we do not use specific patent applications, such as waste management technologies. Therefore, the priority term cannot be calculated in a decomposition analysis for total environmental technology patent applications.

over time. This is because patent applications require novel products. Therefore, the number of available technology items for which patent applications can be filed decreases each year.

Second, the costs of and investments in R&D activities increase when newer technologies are used in further investment. Additionally, the invention of technologies using existing or old technologies becomes more difficult each year. However, the latest technologies and rare materials, such as electron microscopes and rare metals, allow us to find new structures and relationships at extremely minute scales and explore new chemical reactions. In such cases, the equipment and materials needed for experiments require large R&D expenditures. The efficiency factor is defined by the number of total patent applications for a given amount of R&D spending; thus, this expensive R&D produces an indicator that worsens each year, as shown in figure 2.

According to the 2015 Japan Patent Office Annual Report, total patent applications in Japan decreased by 10.8% (42,232 items) from 2008 to 2009. This sharp decline is mainly observed in six technology fields: engineering elements or units, measuring and testing instruments, computing and calculating, general vehicles, electronic communication techniques, and basic electrical elements. The patent applications filed in these six technology fields declined by 16,479 items, which represents a decrease in total patent applications of approximately 40% from 2008 to 2009. The Japan Patent Office Annual Report indicates that the main reason for this dramatic decline is the economic recession triggered by the collapse of Lehman Brothers in 2008. Additionally, R&D expenditures by private companies declined during this period because corporate financial performance, which is strongly related to bankruptcy risk, deteriorated. Therefore, we suggest that the smaller effect of the scale factor after 2008 was due to the financial crisis.

The decrease in the efficiency factor since 2008 is also due to other crisis-related issues: R&D expenditures, including researcher salaries, are difficult to cut immediately during a financial crisis. Researchers in private companies are usually employed in permanent positions, which are strongly protected by the Labor Standard Act in Japan. Meanwhile, the procurement of expensive materials and equipment for R&D activities becomes difficult in an uncertain economic situation or during periods of unstable corporate financial performance. Therefore, private companies cut material and equipment costs but maintained researcher salaries. The gap between researchers and the resources they need to innovate is another reason for the declining efficiency factor after 2008.

<Figure 2 is here>

Next, we discuss the decomposition analysis results for private companies by type of technology. Table 5 represents the change in cumulative patent applications from 2001 to 2010 by type of environmental technology. From table 5, all technology types exhibit similar trends: a negative effect of the efficiency factor and a relatively small effect of the scale factor. Meanwhile, the effects of the priority and environmental patent share factors differ by type of technology.

We identify three trends in the decomposition analysis by focusing on the priority and environmental patent share factors. The first trend observed is in the administrative, regulatory or design aspects of technology field. In this area, patent applications increased mainly due to the stronger effect of the priority factor. One interpretation of this result is that new business opportunities in emission trading systems were created by the Kyoto Protocol in 2005. The creation of a new and large-scale market encouraged private companies to seize these opportunities and to improve their market competitiveness using their R&D resources. Thus, we can explain the increasing number of patent applications for administrative, regulatory or design aspects through the priority factor, which was in turn strongly affected by the Kyoto Protocol.

The second trend is observed in the transportation and energy conservation technology fields. In these two technology areas, patent applications increased mainly due to the growth of the environmental patent share. The priority factor also contributes to the increase in patent applications, albeit weakly. Therefore, the contributions of these two technologies are different from the first trend introduced above. The positive trend in patent applications filed for these two fields is similar to that of environmental technology out of total patent applications.

One interpretation of this trend is that transportation and energy conservation technologies are strongly related to the market competitiveness of products because the operating costs of transportation equipment and electrical products depend on these technologies. Therefore, the incentives for transportation and energy conservation technology innovation become stronger with growing environmental technology demand. Additionally, the demand for environmental technology is widely affected by the cost of energy resources. Because international oil prices increased dramatically from 2001 to 2010, the demand for environmental technology increased. Thus, the increased number of patent applications in these two market competitiveness–related areas was mainly due to the increase in the environmental technology share observed from 2001 to 2010.

The third trend is observed in alternative energy production, waste management, agriculture/forestry, and nuclear power generation technologies. In these four technology areas, priority negatively affected the change in patent applications from 2001 to 2010, especially for waste management and agriculture/forest technologies. The priority factor decreased because the market demand for these technologies decreased in 2010 relative to 2001. During the 1990s and early 2000s, waste management became a key issue for balancing economic development and environmental protection on Japan's small land area. Additionally, many environmental policies, such as the basic environmental law of 1993, the home appliance recycling law of 1998, and the law concerning special measures against dioxins of 2000 have entered into force. Therefore, market demand for waste management was high during this period.

Meanwhile, climate change and Japanese energy security issues became more serious in the late 2000s. These serious environmental and resource problems provide strong incentives to invent energy conservation and climate change mitigation technologies. Thus, one reason for decreasing patent applications in waste management technology from 2001 to 2010 is that the priority technology in corporate R&D strategies shifted from waste management to energy conservation and climate change mitigation due to changes in market demand. This priority change is observed in the Japanese science and technology basic plan. In the 2nd (2001 to 2005) and 3rd (2006 to 2010) basic plans, the creation of a resource-circulating society was a high-priority research field. However, the 4th basic plan (2011 to

2015) set technology related to creating a low-carbon society and efficient energy use through smart infrastructure as high priorities. This policy change by the Japanese government helps explain the priority change in corporate R&D strategy observed from 2001 to 2010.

<Table 5 is here>

Next, we discuss the results for the public sector. Figure 3 represents the results of a decomposition analysis for the period from 2001 to 2010. From figure 3, the efficiency factor strongly contributed to the increase in environmental patent applications until 2007, which is a different trend from that observed for private companies. The contribution of efficiency could have been caused by strengthening business-academic collaborations, which were promoted by the Japanese Bayh-Dole Act in 1999 and the National University Corporation Act in 2003.

Rules governing patent ownership for innovations developed using government research funding were changed by the Japanese Bayh-Dole Act in 1999. After this law entered into force, inventors who used these research funds for R&D activities could obtain ownership of the resulting patents. Therefore, researchers using government funds had strong incentives to invent new technologies and obtain patent ownership (Kato and Odagiri, 2012). Thus, this change in patent ownership could have increased the efficiency factor.

A second reason for the increase in public sector efficiency is a change in the R&D strategies of national universities due to the National University Corporation Act passed in 2003. This Act reclassified national universities as independent administrative entities, which use an independent accounting system. Before this Act, universities focused mainly on student education and academic publication, especially of basic research. However, after the Act entered into force, universities were required to increase their market competitiveness in both education and technology development to secure funding. This R&D strategy change among universities encouraged them to proactively form research collaborations with private companies to publish academic papers and file patents

(Motohashi and Muramatsu, 2012). However, the efficiency factor decreased after 2007. We suggest that the main reason is the global economic recession, as business-academic collaboration is difficult during periods of high financial risk for private companies.

Next, we discuss the change in the environmental technology share for the public sector. During the early 2000s, the share of environmental patent applications decreased. The application shares of several technology fields, such as chemicals, medicine, semiconductors, image communication, and electric digital data processing technologies, increased. However, patent applications related to the emission trading system increased rapidly from 41 items in 2005 to 95 items in 2006, which increased the contribution of the share factor.

Figure 3 indicates that the main change in environmental patent increases in the public sector is due to the efficiency factor rather than the share factor. This finding is detectable only by conducting separate decomposition models for the private and public sectors. The small contribution of the share factor and the high contribution of the efficiency factor are similar in the results according to type of technology described in table 6.

<Figure 3 is here>

As seen in table 6, the priority factor strongly contributes to the increase in patent applications for alternative energy production filed by the public sector. Alternative energy technologies include many basic research fields, such as solar panel materials and biofuel enzymes. As we noted, public sector actors have a comparative advantage in basic research fields. Therefore, public sector actors apply for patents to gain market competitiveness in this field. The government has increased research budgets in the renewable energy field, and R&D strategies are strongly dependent on the research budget allocations of the government. From 2001 to 2010, the Japanese government increased research budgets for renewable energy to achieve a low-carbon society. Thus, we consider these two reasons for the increased role of the priority factor in alternative energy production in the public sector.

Another finding in table 6 is the contribution of the priority factor for administrative, regulatory or design aspects to the dramatic increase in private sector patent applications in this area. Meanwhile, the composition of patent applications changed from 2001 to 2010. Before 2005, the main technology area was commuting technologies, while patent applications for the emissions trading system increased from 2005 to 2006. After 2006, public sector patent applications related to administrative, regulatory or design aspects gradually decreased each year. Therefore, enforcement of the Kyoto Protocol affected the R&D strategy of the public sector, increasing patent applications related to emissions trading over the short term. However, this effect did not persist over the long term, as seen in the private sector results.

<Table 6 is here>

5. Conclusions

This study analyzes the determinants of environmental patent applications in the private and public sectors in Japan. We focus on the different characteristics of each environmental technology type. We apply the LMDI approach to patent application changes from 2001 to 2010 for seven technology groups. Our main findings are summarized as follows.

First, the determinants of environmental patent applications differ between the private and public sectors. Private companies increased environmental patent applications mainly due to their share of environmental patent applications. Meanwhile, the public sector increased applications by improving the number of patent applications filed for given R&D expenditures, that is, it improved the efficiency of R&D activities. This efficiency improvement in the public sector may have been caused by the Japanese Bayh-Dole Act and the strengthening of business-academic collaborations in Japan in the 2000s.

Second, the priority of environmental patents differs in each technology group. Patent applications in the administrative, regulatory or design area increased more than threefold from 2001 to 2010 among private companies. This dramatic increase could have been related to new business opportunities created by the introduction of an emissions trading system by the Kyoto Protocol in 2005. Because private companies fund research through their corporate profits, new business opportunities provide strong incentives to invent new technologies. Therefore, a market designed to create environmental business is important to enhancing private creation of environmental technologies.

Third, the public sector did not react strongly to new business opportunities produced by the Kyoto Protocol. These findings indicate that private companies may be more sensitive than the public sector to market demands for technologies, as public sector R&D strategy depends on the research budget allocated by the government, which is not intended to maximize profits. In other words, R&D activities in the public sector focus on the technology areas in which private companies struggle due to high corporate risk and low profitability. Therefore, the government needs to consider the characteristics of environmental technology during the research budget planning process, especially how these technologies are related to demand in the market over the short term or to demand in society over the long term.

Finally, we consider why the environmental patent application share increased during the lost decades in Japan. The above findings of the decomposition analysis of environmental patent applications suggest three main reasons. The first reason is changes made to rules governing patents. The main changes were produced by the Japanese Bayh-Dole Act in 1999 and the National University Corporation Act in 2003. These two acts provide strong incentives for research institutes, which accept research funding from the government, to file patent applications in order to survive in the market during economic depressions.

A second reason is the growth of market demand for environmental technologies, especially for climate change mitigation, due to international environmental policies. These policies create new business markets in which private companies gain competitiveness if they develop higher quality patented products. Thus, we argue that the growth of the share of environmental patents from 2005 to 2006 was caused by private companies' quick response to the enforcement of the Kyoto Protocol, which made the emissions trading system a high priority.

A third reason is that the relative priority of environmental technology increased due to the economic recession triggered by the collapse of Lehman Brothers in 2008. During financial crises, companies reduce their R&D activities. Meanwhile, the Japanese government started the eco-point system and granted subsidies for eco-friendly cars as part of its emergency economic measures. These policies provided strong incentives for private companies to invent technologies for energy conservation and transportation. Therefore, the share of environmental patents increased after 2008 due to the re-prioritization of certain technologies, especially in the energy conservation and transportation technology fields.

These findings explain why environmental patent applications increased during the economic recession in Japan, which is useful for establishing effective environmental policies and allocating government research budgets to achieve sustainable development. Additionally, the research framework and application of a decomposition model for patent invention could be helpful for estimating the determinants of R&D activities and for conducting policy evaluations. We suggest that policy makers and decision makers within companies' R&D divisions apply this R&D decomposition research framework to evaluate the effects of subsidies and policies on environmental technology innovation. The results imply that policies and subsidies affect the invention of environmental technologies through the four determinant factors. This information is helpful in forecasting how policy may affect future environmental technology inventions.

Further research is needed on the following two points. First, factor decomposition analysis that considers the time-lag between investment and patent invention is needed. The time-lag span between environmental inventions and patents is diverse and depends on the characteristics of patent technology. Therefore, it was difficult for our research framework to clearly consider the time-lag effect, which is an important factor in understanding patent invention activities.

Second, future research should include a comparative analysis of developed and developing countries. Such an analysis could clarify the priority gap in the R&D strategies of each environmental technology type. Based on the determinants of each environmental technology area, we can suggest effective domestic and international policies to enhance the development of future environmental technologies for a sustainable society.

Acknowledgements

This research was funded by the Grant-in-Aid for Specially Promoted Research [26000001B]; the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan; and Grant-in-Aid for Research Activity Start-up [26881006B], MEXT, Japan; and research program “Policy studies of environmental economics” by the Japanese Ministry of the Environment. The results and conclusions of this article do not necessary represent the views of the funding agencies.

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Table 1. Policies and international events related to environmental technology inventions

Year	Japanese policies and international events
1990-1994	- Business council for sustainable development created (1990) - United Nations conference on environment and development (1992) - Law concerning special measures for total emissions of nitrogen oxides and particulate matter reductions in Japan (1992) - Convention on biological diversity (1993) - Basic environmental law in Japan (1993) - Framework convention on climate change (1994) - The basic environmental plan in Japan (defined concept of environmental risk) (1994)
1995-2000	- ISO14001 certificate started (1996) - Environmental impact assessment law in Japan (1997) - Kyoto Protocol adopted (1997) - Home appliance recycling law in Japan (1998) - Law concerning the promotion of measures to cope with global warming in Japan (1998) - Act on special measure for industrial revitalization (Japanese Bayh-Dole Act) (1999)
2000-2004	- Cartagena Protocol on biosafety (2000) - Basic law for establishing a recycling-based society in Japan (2000) - Act on promoting green purchasing in Japan (2000) - Law concerning special measures against dioxins in Japan (2000) - World summit on sustainable development (2002) - Amendment of chemical substances control law in Japan [introduced concept of environmental risk impact into ecological system] (2003)
2005-2010	- Kyoto Protocol entered into force (2005) - Effect on RoHS directive (2006) - Amendment of air pollution control law in Japan [emissions restrictions on VOCs] (2006) - Eco-point system for energy-saving electric products in Japan (2009) - Government subsidy program for eco-friendly cars (2009) - Carbon emission trading system is started in Tokyo, Japan (2010)

Table 2. Breakdown of patent application and R&D expenditures of private company and public sector

Year	Patent application		R&D expenditure		Breakdown of R&D expenditure					
					Private company			Public sector		
	Company	Public sector	Company	Public sector	Basic research	Applied research	Development	Basic research	Applied research	Development
2001	99%	1%	76%	24%	6%	20%	74%	42%	33%	25%
2002	99%	1%	75%	25%	6%	20%	75%	43%	33%	24%
2003	98%	2%	76%	24%	6%	19%	75%	43%	34%	23%
2004	98%	2%	76%	24%	6%	19%	75%	41%	35%	25%
2005	98%	2%	77%	23%	6%	20%	74%	41%	34%	25%
2006	98%	2%	78%	22%	7%	19%	75%	40%	35%	26%
2007	98%	2%	79%	21%	6%	20%	74%	41%	35%	25%
2008	97%	3%	78%	22%	6%	20%	74%	40%	35%	25%
2009	98%	2%	75%	25%	7%	21%	73%	41%	35%	24%
2010	97%	3%	76%	24%	7%	19%	74%	40%	35%	25%

Note: To compare the patent application between company and public sector, the share of patent application is estimated by using number of application of company and public sector as denominator. In this sense, we did not count the individual patent application for denominator.

Source: Survey of Research and Development (http://www.stat.go.jp/english/data/kagaku/index.htm)

The Institute of Intellectual Property patent database.

Table 3. Description of environmental patent group

Patent group	Patent subgroup
Alternative energy production	(1) Bio-fuels, (2) Integrated gasification combined cycle fuel cells, (3) Pyrolysis or gasification of biomass, (4) Harnessing energy from manmade waste, (5) Hydro energy, (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, e.g., natural heat, (11) Using waste heat, (12) Devices for producing mechanical power from muscle energy
Transportation	(1) Vehicles in general, (2) Vehicles other than rail vehicles, (3) Rail vehicles, (4) Marine vessel propulsion, (5) Cosmonautic vehicles using solar energy
Energy 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
Waste management	(1) Waste disposal, (2) Treatment of waste, (3) Consuming waste by combustion, (4) Reuse of waste materials, (5) Pollution control
Agriculture/Forestry	(1) Forestry techniques, (2) Alternative irrigation techniques, (3) Pesticide alternatives, (4) Soil improvement
Administrative, regulatory or design aspects	(1) Commuting, e.g., HOV, teleworking (2) Carbon/emissions trading, e.g., pollution credits (3) Static structure design
Nuclear power generation	(1) Nuclear engineering (2) Gas turbine power plants using heat source of nuclear origin

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

Table 4. Share of environmental patent applications by industry and public sector from 2001 to 2010

	Private company				Public sector		
	Electric products	Transportation equipment	General machinery	Chemical products	Universities	Research institutes	Government
All environmental patents	29.8%	17.5%	6.7%	3.5%	39.0%	54.9%	6.1%
Alternative energy production	25.9%	22.2%	7.2%	4.5%	42.9%	51.7%	5.4%
Transportation	6.6%	60.5%	5.3%	0.1%	39.8%	59.0%	1.2%
Energy conservation	47.0%	8.5%	1.5%	3.3%	43.0%	54.2%	2.8%
Waste management	10.1%	19.3%	16.7%	4.7%	32.1%	56.1%	11.8%
Agriculture/Forestry	1.7%	1.2%	6.5%	23.9%	37.3%	44.8%	17.9%
Administrative, regulatory or design aspects	34.6%	14.9%	2.0%	0.4%	39.2%	57.4%	3.4%
Nuclear power generation	49.5%	1.3%	15.6%	0.1%	12.7%	87.3%	0.0%

Table 5. Change in private company patent applications by technology type from 2001 to 2010

	Patent application change		Decomposed factor contribution			
	(item)	(%)	Priority	Envshare	Efficiency	Scale
All environmental patents	1,930	12%	N.A.	65%	-58%	5%
Alternative energy production	88	2%	-13%	65%	-57%	7%
Transportation	191	47%	35%	80%	-69%	2%
Energy conservation	1,338	31%	18%	67%	-59%	4%
Waste management	-2,222	-49%	-59%	39%	-37%	8%
Agriculture/Forestry	-85	-59%	-61%	27%	-28%	6%
Administrative, regulatory or design aspects	2,676	326%	313%	198%	-176%	-9%
Nuclear power generation	-56	-14%	-23%	40%	-37%	5%

Table 6. Change in public sector patent applications by technology type from 2001 to 2010

	Patent application change		Decomposed factor contribution			
	(item)	(%)	Priority	Envshare	Efficiency	Scale
All environmental patents	96	23%	N.A.	-2%	20%	5%
Alternative energy production	121	92%	65%	1%	21%	6%
Transportation	-5	-45%	-47%	-7%	4%	4%
Energy conservation	32	41%	22%	2%	13%	4%
Waste management	-37	-33%	-66%	-4%	33%	4%
Agriculture/Forestry	7	140%	89%	1%	47%	2%
Administrative, regulatory or design aspects	-8	-12%	-13%	-6%	2%	4%
Nuclear power generation	-14	-58%	-79%	-10%	27%	3%

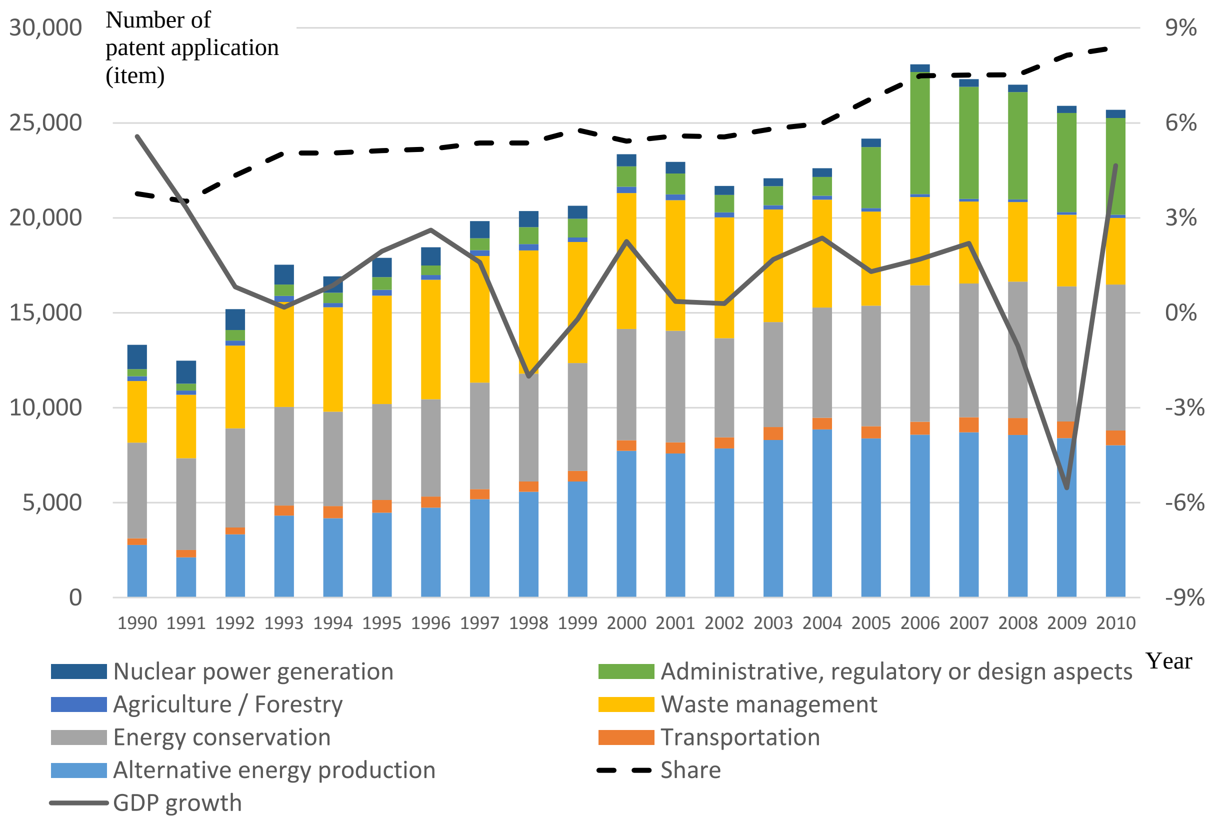

Figure 1. Trends in Japanese environmental patent applications by type of technology

Source: Patent data are from patent database published by the Institute of Intellectual Property, GDP growth is from World Development Indicators published by the World Bank.

Note: The share is calculated as the number of environmental patent applications / number of total patent applications.

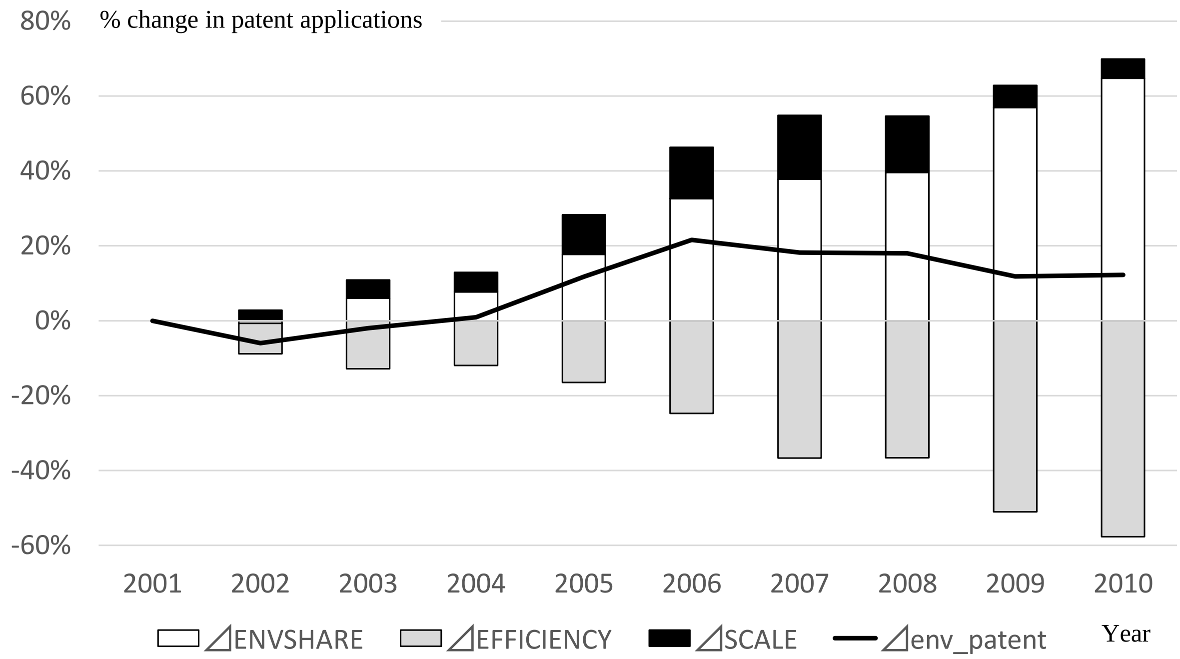

Figure 2. Results of decomposition analysis for private companies' environmental patent applications

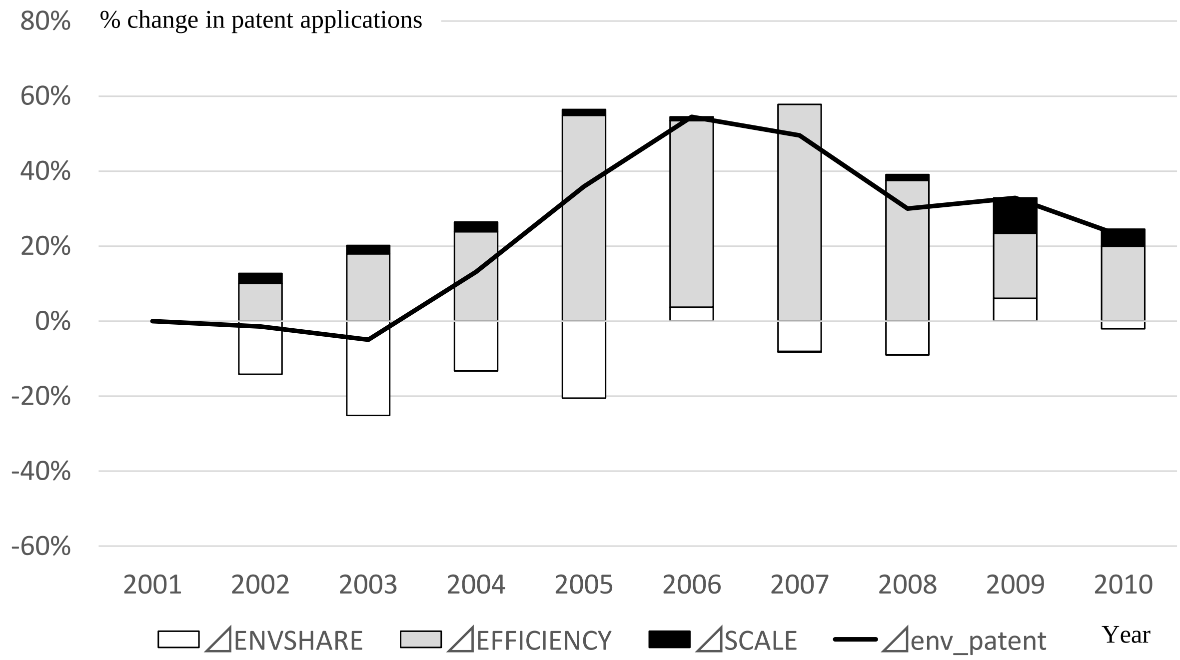

Figure 3. Results of decomposition analysis for public sector actors' environmental patent applications