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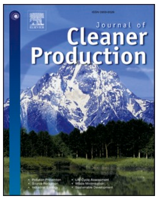

The drivers of private and public eco-innovations in six large countries

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ABSTRACT

The purpose of this paper is to examine and compare the contributions to environmental innovation of the public sector and private sector, respectively, and to compare their determinants. We analyze the development over time of triadic patents, classified as environmental technological innovations, for six major patenting countries from 1990 to 2014. This is done using a factor decomposition analysis framework. The analysis is done at both country aggregate level, and for a set of specific technological topics: alternative energy production, energy conservation, agriculture and forestry, and waste management. Results indicate that there has been a shift at an aggregate level towards environmentally sustainable technologies. In the private sector, the shift can be attributed to changes in research priorities and an increased scale of R&D. In the public sector, increased patenting of environmentally sound technologies can be attributed to efficiency gains. The largest difference between the public and private sector is observed in R&D efficiency, where in the private sector, reductions in efficiency have contributed negatively to patent growth, whereas the opposite is true for the public sector. In both sectors, research focus has shifted towards energy-related technologies.

1. Introduction

Technological innovation is an integral part of economic development, and a necessary condition for creating an environmentally sustainable society and limiting climate change (European Commission, 2011; Popp, 2019; The White House, 2021). The private sector is frequently argued to be generally more suitable for innovation, based on the efficiencies associated with market forces and competition (Archibugi and Filippetti, 2018). Consequently, it has been suggested that the public sector's research and development (R&D) should be downscaled (David et al., 2000). However, many studies also argue that public sector research is necessary for achieving large societal gains (Archibugi and Filippetti, 2018). In practice, the public sector's innovation as a fraction of GDP has been shrinking over time in most OECD countries: the share of gross expenditure on R&D by governments in OECD declined from 44% in 1981 to 28% in 2013 (Archibugi and Filippetti, 2018). However, there is limited knowledge about the associated impact on the development of different types of novel technologies, long-term economic growth, and social welfare (Conceiçao et al., 2004).

Given the increased emphasis by policy makers on environmentally sustainable technologies as a tool to solve climate change and natural resource problems at global scale, it is important to understand the roles of the public and the private sectors and their contribution to environmental innovation. As argued by Popp (2019), public/private sector comparisons have not received enough attention in this context, given that information on the potential role of the two sectors would be valuable to understand how policy priorities can be reflected in R&D activity. Methods for evaluating innovation performance are essential for such comparisons. However, in their review of studies on public sector innovation across all policy fields, De Vries et al. (2016) find that 76% of the studies lack a formal or precise definition of the innovations studied. This illustrates the need for using clearly defined measures and concepts when comparing the two sectors. In addition, De Vries et al. (2016) emphasize the need for more quantitative studies, and cross-national and cross-sectoral comparisons.

The purpose of this paper is to examine and compare the contributions to environmental innovation of the public sector and private sector, respectively, and to compare their determinants. We focus specifically on the drivers of environmental technological innovation. The drivers of technological innovation could differ from those of, for example, process innovation, innovations new only to the particular firm, or business model innovations, which are not studied here.

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Environmental technological innovations are a subset of all technological innovations, including technologies that are expected to reduce the environmental impact of consumption or production activities (del Río et al., 2016).

To measure environmental technological innovation, we use patents as an indicator. Further, innovations are classified as being either public or private based on the type of organization to which the patentee or applicant belongs; for example, a patent filed by a university would be considered a public innovation.[1] We identify the role of different drivers by decomposing patent applications related to environmental innovation into different components explaining the research process. We then examine each component's relative impact on the patenting of environmental innovation, both across the two sectors and across major topics of green technology: alternative energy production, energy conservation, agriculture and forestry, and waste management.[2] For this purpose, we use the Logarithmic Mean Divisia Index (LMDI) to decompose triadic patent applications, which are patents simultaneously filed at three major patent offices in the EU, Japan, and the United States,[3] for six major patenting countries from 1990 to 2014 into: *(i)* priority of technological field, *(ii)* environmental patent share, *(iii)* efficiency of R&D, and *(iv)* scale of R&D. Based on the literature, we expect that private sector R&D is more efficient than public sector R&D (Archibugi and Filippetti, 2018; David et al., 2000), and has a stronger focus on technological fields closer to the market (Archibugi and Filippetti, 2018). Further, we examine whether environmental research priorities have changed over time and if this change differs between the private and public sectors. In particular, environmental policy focus has, over time, shifted toward climate change–related issues, which we expect to be reflected in the time trend.

Few previous studies have investigated the quantitative differences in environmental innovation between the public and private sectors. Fujii and Managi (2016) studied the topic using Japanese data but did not use triadic patents and, hence, they did not distinguish between more and less valuable technologies. Also, their study is not clear on the treatment of home bias, which is a concern when using patent data for the purpose of international comparisons since patent applicants are more likely to file the own national or regional patent office. Hence, only using patent from one such office would yield biased results. Additionally, they assigned patents to sectors based on the first applicant, which can introduce systematic errors. Thus, this paper contributes by comparing the private and public sector innovations in major innovating countries. The relevance of the comparison is enhanced by the use of a clearly defined quantitative measure of innovation, triadic patents, which implies that the focus is set on valuable technologies.

The paper is organized as follows: in Section 2, we provide a theoretical background, and in Section 3, we describe our methodological framework. Section 4 provides a description of the data, and Section 5 presents the result of our LMDI calculations. This is followed by a discussion of the result in Section 6 and concluding remarks in Section 7.

2. Theoretical background

The literature shows that the private and public sectors differ in their characteristics as well as in the incentives driving the R&D process. The differences with respect to financing, goals, and aims of new R&D, can affect the type of technologies developed. For example, individual firms might not be willing to fund the R&D process for technologies where the benefits are widespread but either uncertain or long-term (Conceiçao et al., 2004), as the private sector innovates to seek and ensure future profits. In contrast, the public sector can aim to innovate to increase social welfare, and innovation is typically financed either by a national innovation fund or by the central budget (OECD, 2017). Consequently, governments tend to focus relatively more on basic research, and on technologies which have an infrastructural, quasi-public good character (Tassey, 2004). Differences in costs, market structure, and competitiveness, can further affect R&D decision and environmental innovation across the private and public sector (Fujii and Managi, 2016).

The private sector's drivers of environmental innovation are widely studied, and can be divided into those that coincide with the ones for innovation in general and other determinants that are specific to environmental innovation (del Río et al., 2016). As shown by Acemoglu et al. (2016), R&D decisions are generally motivated by future discounted profits, and the direction that research takes is partly determined by changes in relative prices. Thus, demand plays an important role. However, market pricing processes need not lead to socially optimal incentives for innovation. In particular, this is the case for environmental innovation, where the presence of two different market failures cause a so called double externality problem. First, knowledge creation and innovation have to a certain degree characteristics similar to public goods (Geroski, 1995): for the technology to yield a profit, the innovator must make it known to the public. This creates spillover effects, allowing others to benefit from the knowledge and create additional innovations (Popp and Newell, 2012), thereby reducing the potential profits of the original innovator. In line with this, Acemoglu et al. (2016) show that if dirty technologies are more advanced than clean ones, this reduces the private sector innovation in clean technology, favoring the dirty because the average profits for the clean technology are lower. Second, the market provides too weak incentives for environmentally friendly technologies to develop, because firms' and households' cost of pollution is below the social cost. Together these market failures imply that private firms' environmental innovation is below what is socially optimal, reducing R&D activities (Popp, 2019). Suggested solutions include suitably designed environmental regulations, targeted public R&D funding and research subsidies, and private-public collaboration, which can strengthen the incentives for environmental innovation (Horbach, 2008; Horbach et al., 2012; Triguero et al., 2013; Acemoglu et al., 2016; Häggmark and Elofsson, 2021).

3. Method

To establish if there is a difference in environmental innovation in the public versus the private sector, we use a decomposition analysis framework, LMDI, derived in Ang et al. (1998). This framework is widely used to analyze changes over time at an aggregate, economy-wide level. The method is applied in different fields; energy use and intensity studies (Forin et al., 2018; Román-Collado and Colinet, 2018; Torrie et al., 2016; Voigt et al., 2014), tracking CO_2 emissions

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[1] This issue is further discussed in the Data chapter where the method of classification is explained, and Table 1 shows the correspondence between sector and organization.

[2] The technological topics analyzed follows from the IPC Green Inventory and their categorization of technologies. Technologies included are regarded as environmentally sound technologies.

[3] Triadic patents are patents which are filed simultaneously to the three major patenting offices for the same innovation: United States Patent and Trademark Office (USTPO), European Patent Office (EPO) and the Japan Patent Office (JPO). Using triadic patents overcomes some of the issues related to using patent counts as an indicator for technological innovation, se Section 4 for a more detailed discussion.

(Cansino et al., 2018; Chen et al., 2019; Shahiduzzaman et al., 2015; Wang and Feng, 2018), water use and food production (Ang, 2015; Hawkins et al., 2018; Liu et al., 2014), economic growth (de Freitas and Kaneko, 2011), and material use (Pothen and Schymura, 2015). Specifically for technological change and patent analysis, decomposition analysis has been applied by Fujii (2016) and Fujii and Managi (2016) in analyzing innovation in Japan. Once the researchers have defined the variable of interest, for example the number of patents or total CO_2 emissions, the framework allows for decomposition of this variable into a set of factors determining the generation process.

3.1. Logarithmic mean divisia index (LMDI)

The LMDI procedure is here applied to eco-innovations in the private and public sectors, respectively. Our variable of interest is environmental patent activity in a specific technological field.[4] Below, we derive the model for a specific technology, but we also carry out the decomposition procedure at an aggregate level for all environmental technologies. To begin, we have patent applications for technology field i in country j at a given time t, defined by equation (1):

$$\text{Env. Pat. Application}_{i,j,t} = \frac{\text{Env. Pat. Application}_{i,j,t}}{\sum_{i=1}\text{Env. pat. Application}_{i,j,t}} \times \frac{\sum_{i=1}\text{Env pat. Application}_{i,j,t}}{\text{Total Pat.}_{j,t}} \times \frac{\text{Total Pat.}_{j,t}}{\text{R\&D}_{j,t}} \times \text{R\&D}_{j,t}, \tag{1}$$

which is an identity. The right-hand side terms have a natural interpretation, allowing us to reformulate equation (1) as follows:

$$\text{Env.Pat.Application}_{i,j,t} = \text{Priority}_{i,j,t} \times \text{Environmentalshare}_{j,t} \times \text{Efficiency}_{j,t} \times \text{Scale}_{j,t}.$$

For our empirical application we have a year indicator t, with $t \in (1990, 2014)$. The index i, with $i = 1, \ldots, 4$, indicates the technology field, and the index j, with $j = 1,\ldots,6$, indicates the country. The factor *Priority*$_{i,j,t}$, is the share of technology i over the total number of environmental innovation patent applications in country j at time t, thus indicating the specific priority for environmental technology i. This variable increases in value if the patent applications of technology i increase faster than does the total number of environmental innovation patent applications, implying that the priority of researching the technology field i has increased. Note that the priority variable will be suppressed in the aggregate model. The factor *Environmental share*$_{j,t}$, is the total number of environmental innovation patent applications across all technological topics divided by the total number of patent applications. This yields the share of environmental innovation patent applications of the total patent volume. The variable increases if the number of environmental innovations increases more rapidly than does overall patent activity, signaling a higher focus on environmental innovations. The factor *Efficiency*$_{j,t}$, reflects the efficiency of R&D activities and is the total number of patent applications divided by aggregate expenditure on R&D. R&D expenditure is used as input into innovation activities. For example, if the number of patents goes up while R&D stays constant, the efficiency of the research process has increased. The factor *Scale*$_{j,t}$, is the total aggregate R&D expenditure, included to account for scale effects in expenditure on R&D.

We are interested in the growth ratio of environmental innovation patent applications over time.[5] Let y be the environmental patent applications for technology i, and consider the change from period $t-1$ to period t. Formulating equation $(1')$ as growth ratios then yields the expression in equation (2):

$$\frac{y_{i,j,t}}{y_{i,j,(t-1)}} = \frac{\text{Priority}_{i,j,t}}{\text{Priority}_{i,j,(t-1)}} \times \frac{\text{Environmental share}_{j,t}}{\text{Environmental share}_{j,(t-1)}} \times \frac{\text{Efficiency}_{j,t}}{\text{Efficiency}_{j,(t-1)}} \times \frac{\text{Scale}_{j,t}}{\text{Scale}_{j,(t-1)}} \tag{2}$$

Taking the natural logarithm of both sides yields equation (3):

$$\ln\left(y_{i,j,t}\right) - ln\left(y_{i,j,(t-1)}\right) = ln\left(\frac{\text{Priority}_{i,j,t}}{\text{Priority}_{i,j,(t-1)}}\right) + ln\left(\frac{\text{Env. share}_{i,j,t}}{\text{Env. Share}_{i,j,(t-1)}}\right) + ln\left(\frac{\text{Efficiency}_{i,j,t}}{\text{Efficiency}_{i,j,(t-1)}}\right) + ln\left(\frac{\text{Scale}_{i,j,t}}{\text{Scale}_{i,j,(t-1)}}\right) \tag{3}$$

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[4] Table A1 in the Appendix lists technological topics classified as environmentally sustainable technologies.

[5] The LMDI approach is robust to zero values in the data (Ang et al., 1998), and can, therefore, handle cases in which countries have zero patent applications in a given year. A zero is replaced using a small positive value, shown in Ang and Liu (2007) to not influence the result.

Multiplying both sides by $\theta_{i,j,t} = \frac{y_{i,j,(t-1)} - y_{i,j,(t-1)}}{(\ln y_{i,j,t} - \ln y_{i,j,(t-1)})}$ yields the following

$$y_t - y_{t-1} = \Delta y_{t,t-1} = \theta_t ln\left(\frac{\text{Priority}_t}{\text{Priority}_{t-1}}\right) + \theta_t ln\left(\frac{\text{Env. share}_t}{\text{Env. share}_{t-1}}\right) + \theta_t ln\left(\frac{\text{Efficiency}_t}{\text{Efficiency}_{t-1}}\right) + \theta_t ln\left(\frac{\text{Scale}_t}{\text{Scale}_{t-1}}\right), \tag{4}$$

equation (4), which describes the change in environmental innovation patent application technology *i* in country *j*.[6]

where θ_t is an additive weight, and $\Delta y_{t,t-1}$ is the change in environmental patent applications for technological field *i* in country *j*. The four right-hand side terms in equation (4) thus correspond to the right-hand side elements of equation (1), and equation (4) is used to track and decompose the change in patent applications over time into the specified elements.

4. Data

The dataset used in this paper was compiled from several sources. The countries included in the study are China, France, Germany, Great Britain (GB), Japan, and the United States (US). The US, Japan, and Germany are responsible for most of the triadic patent applications, and the six countries have, between them, approximately 84% of the total patent volume. The patent counts are based on the PATSTAT database. The final dataset covers the period from 1990 to 2015 and contains a total of 991 355 patents of which 156 193 are classified as green patents (i.e., 16%). Approximately 5% of the total number of patents are classified as belonging to the public sector. Table A1 in the Appendix gives an overview of the patents counts distribution across private and public and green patents.

The International Patent Classification (IPC) describes technological innovations and classifies them into different technology topics according to their technological attributes. Each technological topic contains several technological subgroups. Thus, each technology patent in the PATSTAT database has one or several associated IPC classifications. Moreover, the IPC Green Inventory, which was developed by the committee of experts of the World Intellectual Property Organization (WIPO), identifies the subset of IPC codes that can be classified as Environmentally Sound Technologies in line with the United Nations Framework Convention on Climate Change. In this paper, we use the list of technologies provided in the IPC Green Inventory to classify patents in our dataset as green, i.e., as environmental innovations. The environmental technological topics analyzed are: alternative energy production, energy conservation, agriculture and forestry, and waste management, thus following the IPC Green Inventory classifications by the WIPO. A couple of additional technological topics can be found in the IPC Green Inventory: nuclear power generation, administrative, regulatory or design aspects and transportation. These topics had very few patents classified, and it is therefore not meaningful to analyze the development of these topics individually, but these patents are included in the aggregated analysis. Details on technological subgroups included in each technological topic are provided in Table A2 in the Appendix.

Table 1
Groups of applicants and sector assignment.

Group	Sector
Company	Private
Government non-profit company	Public
Company hospital	Private
Company university	Private
Government non-profit	Public
Government non-profit university	Public
Hospital	Public
Individual	Private
University	Public
Unknown	–

The data on R&D expenditure is collected from Eurostat's database and is defined as gross domestic expenditure on R&D by sector of performance, regardless of the source of funds. The expenditure data are partitioned on business enterprise sector, private non-profit sector, higher education sector, and government sector. Thus, the first two are expenditure by the private sector, whereas the two latter correspond to public sector expenditure. The R&D expenditure data are in 2015 prices.[7]

4.1. Classifying patents as public or private

It is well known that it can be difficult to classify patents based on the patentee name or applicant name due to variations in how names are written on the patent, and because individuals and organizations can appear under variations of their name, especially over time (du Plessis et al., 2006). In this study, patents are classified as belonging to either the public sector or private sector based on what sector the patentee or applicant belongs to. Thus a private (public) innovation corresponds to a

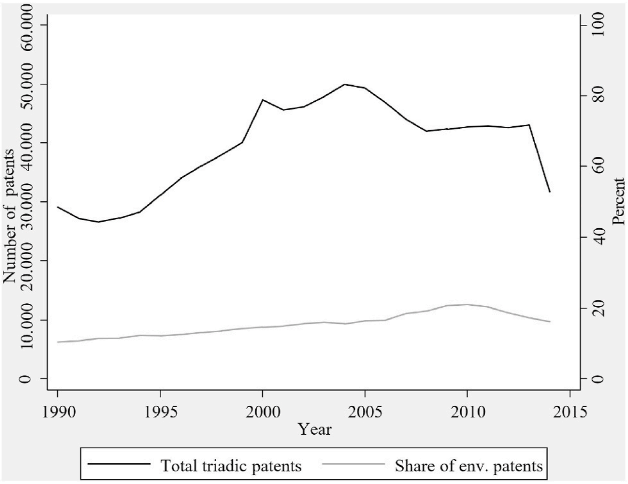

Fig. 1. Triadic patents for the six studied countries for 1990–2014, number of total patents (left y-axis) and share of environmental patents (right y-axis).
Note: Includes data for the studied countries: China, France, Germany, GB, Japan, US. Data source is the OECD Triadic Patent Families Database, based on authors' calculations. The dark line follows left y-axis, and the light grey follows right y-axis.

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[6] Subscript *i* and *j* are dropped for simplicity. Equation (4) is calculated for each respective technology and country.

[7] The expenditure data is deflated using consumer price indices from Eurostat.

Table 2
Results from factor decomposition with LMDI.

Country	Decomposition Factors 1990–2014			Change in patent applications	
	Panel A: Private Sector				
	ΔEnv. share	ΔEfficiency	ΔScale	Δy	Δy (#)
China	10%	−92%	141%	59%	71
France	13%	−63%	41%	−8%	−16
Germany	48%	−71%	48%	25%	115
GB	69%	−64%	18%	23%	26
Japan	134%	−28%	96%	202%	1509
US	27%	−72%	56%	11%	135
	Panel B: Public Sector				
	ΔEnv. share	ΔEfficiency	ΔScale	Δy	Δy (#)
China	20%	64%	257%	341%	7
France	68%	135%	40%	243%	104
Germany	44%	105%	140%	289%	42
GB	34%	−38%	43%	39%	10
Japan	−1%	524%	92%	615%	103
US	−9%	−21%	44%	14%	27

Note: Columns correspond to decomposition factors, and Δy is the left-hand side variable of equation (4), i.e. the change in patents.

patent being filed by a patentee belonging to an organization classified as a private (public) organization (see Table 1). Specifically, this definition follows from the ECOOM-Eurostat-EPO PATSTAT Person Augmented Table Database. The methods used to develop this database were developed by EUROSTAT, KU Leuven, and SOGETI, and are described in du Plessis et al. (2006) and Magerman et al. (2006). The classification method is based on a rule-based logic assuming that information contained in the names of applicants can provide “clues” as to which sector the applicant belongs (du Plessis et al., 2006). These clues refer to parts of company names, legal forms (for example, Inc. or Ltd), or specific words such as government. However, only using these criteria is not sufficient for a satisfactory level of the total patent volume being classified, therefore additional principles are introduced in the classification process. First, if the entity is associated with a large amount of patents, and the first step does not work, sectors are allocated on case-by-case decision. For patentees with more than three patents assigned to them, additional validation efforts are used, yielding a set of case-oriented rules (for a detailed description of the method see du Plessis et al. (2006) and Magerman et al. (2006)). The accuracy of the method was evaluated in Magerman et al., (2006) and was shown to successfully classify more than 99% of the patent volume at both the European Patent Office (EPO) and the United States Patent and Trademark Office (USTPO). The high percentage of patents that have been classified makes the above-mentioned database suitable for our paper. The database assigns patent applicants into the groups listed in Table 1. The ‘unknown’ group is not included in our analysis.

4.2. *Triadic patents*

A patent family is defined as a set of patents filed in different countries to protect the intellectual property of the same innovation. Triadic patents are identified by tracing and matching subsequent patent filings back to an original filing. The date of the original filing of the patent is used to indicate the year in which the patent was submitted. Thus, a patent family consists of a domestic and a foreign patent filing for the same innovation and protection is granted from the original filing. A Triadic Patent Family (TPF) is defined by the OECD as a set of patents filed at the EPO, the USTPO, and the Japan Patent Office (JPO).

We use triadic patents as the unit of analysis since a TPF is usually made up of high-valued patents (van Zeebroeck, 2011), and thus improves the quality of using patents as indicator for innovation and remedies the issues associated with the patent value distribution being skewed towards lower-valued innovations (Dernis and Khan, 2004; Griliches, 1990). Filing for a triadic patent costs more than filing at only the local patent office, hence the expected value of the patent should be higher. Further, using triadic patents overcomes some of the limitations with using single-office patent indicators, such as home bias which can skew the results when doing international comparisons (Dernis and Khan, 2004). For example: an American applicant is more likely to file for patent at the USTPO compared to the EPO or JPO. Conducting an international comparison based on only one patent office would thus risk influencing the robustness of the results when discussing country trends. The dataset used for calculating the triadic patent counts in this paper is extracted from the OECD Triadic Patent Families Database, which, in turn, is based on EPO’s Worldwide Statistical Patent Database and PATSTAT. The patent families in this database have been consolidated to avoid double counting, and both direct and indirect linkages are considered when creating a patent family. Patents are assigned to countries depending on the origin of the applicant. Assigning patents to the private or public sector is done by matching the OECD Triadic Patent Families Database to the ECOOM-Eurostat-EPO PATSTAT Person Augmented Table Database described in the previous section. If there are several applicants from different countries, the patent is assigned proportionally to the number of applicants.

Fig. 1 shows the development of triadic environmental innovations. The share of environmental innovations increased from approximately 10% in the 1990’s, reach 21% of all triadic patents in 2010. Thereafter, the share declined to 16%in 2014.

5. Results

First, result from the aggregate LMDI model for all environmental patents are shown in Table 2, illustrating the accumulated change in environmental triadic patents. The first three columns show the contribution of the different components in the LMDI model to the change in environmental patenting.[8] The fourth column reports the accumulated change in environmental patents, Δy, in percentages, where a positive score indicates increases in environmental patent applications, and a negative score indicates a decrease, over the studied period. Column five gives the change in environmental patents in absolute numbers.

The change in environmental triadic patent applications is positive for both private and public sectors in almost all cases for the period 1990 to 2014, with France as an exception. In France, the number of patent applications by private entities decreased by approximately 8%. Japan stands out, with Δy being 202% for the private sector.[9] The US, GB, and Germany increased their environmental patent activity by 11%, 23%, and, 25%, respectively, and China’s increased by 59%.

The LMDI result on the left hand side of Table 1 shows the driving forces behind these aggregate changes in patent applications between 1990 and 2014. For the private sector, the overall increase has been affected positively by the Δ*Env. share*, indicating that researchers have focused more on developing environmental technologies than on other types of technologies. The scale of R&D activities has also had a positive effect across all countries, as indicated by the positive value of Δ*Scale*. The factor Δ*Efficiency* has a negative score, and, thus, the efficiency for R&D devoted to environmental technologies has decreased, having a negative effect on the aggregate number of environmental patents.

For the public sector, substantial increases are observed for China, France, Germany, and Japan, along with moderate increases for GB and

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[8] Hence, the priority variable is not calculated, because it relies on the technology-specific patent applications.

[9] A notable policy change in Japan to the rules and regulation governing ownership and property rights on innovation were implemented in 1999. Legislation similar to the U.S Bayh-Dole act was adopted (Fujii and Managi, 2016). Researchers could now claim patent ownership of innovations when using government funds, hence increasing the incentives create new technologies.

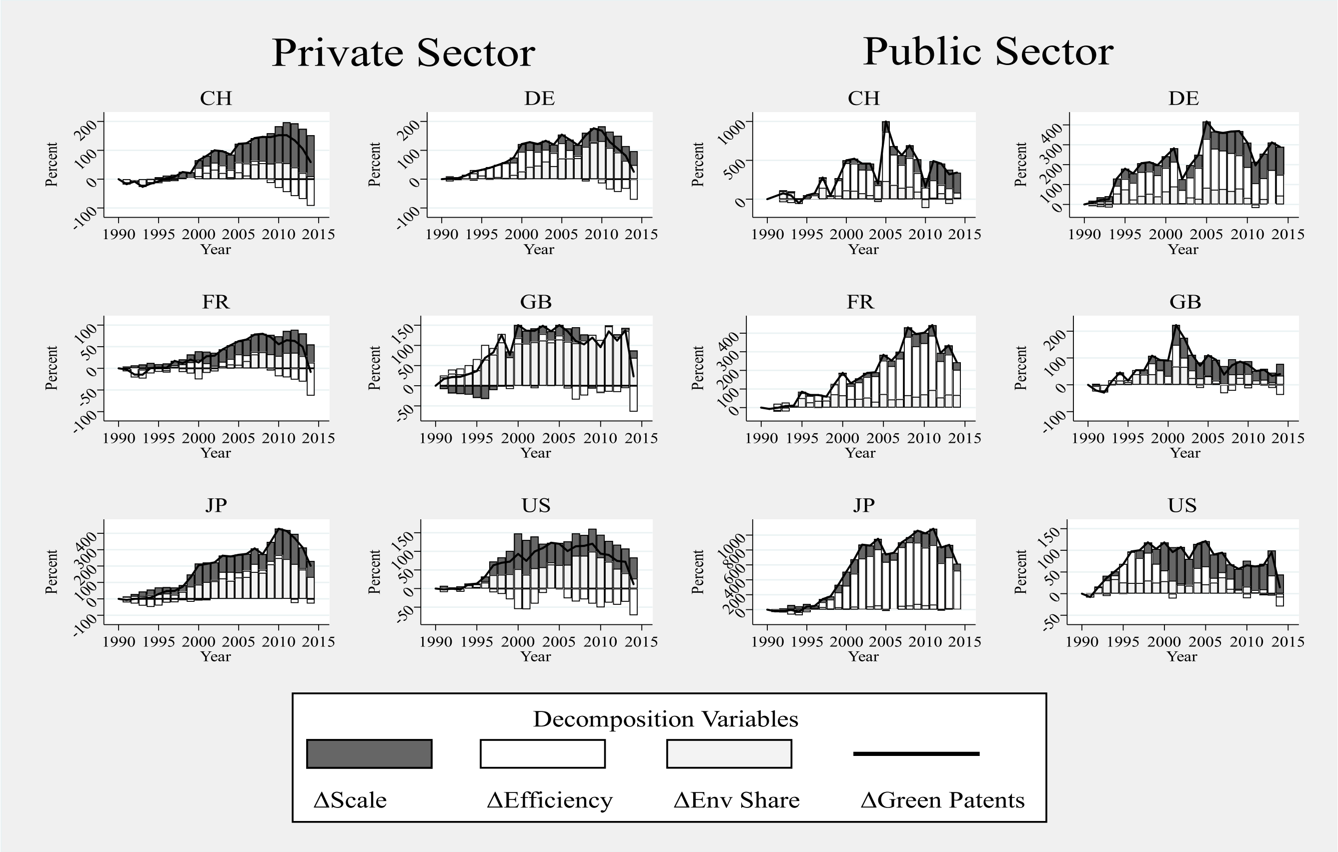

Fig. 2. Aggregate yearly LMDI decomposition result for 1994–2014.
Note: CH = China, DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. The individual impacts of each decomposition factor are stacked on each other. The plotted line sums to the total effect of the stacked bars. The first two columns correspond to the result for the private sector, whereas the third and fourth columns are the result for the public sector. The y-axis indicates percentage changes.

the US, as indicated by Δy in panel B of Table 2. The Δ*Env. share* is small and negative for Japan and the US, indicating that the development of environmental patents has been relatively smaller than the total amount of patents. However, for the other four countries, Δ*Env. share* is positive, indicating that environmental technologies have been increasing more rapidly than other technologies. The scale of R&D activities have a positive effect on environmental patent application growth. Contrary to the private sector, Δ*Efficiency* is positive for most of the countries, except GB and the US.

The development of the decomposition factors over time can be seen in Fig. 2. The bars in the figures are stacked, implying that the plotted curve, Δ*Green Patents*, shows the percentage change in patent applications in each year.[10] The increased importance of environmental technologies is visible in the bar charts, as the Δ*Env. share* starts from a low level and increases until about 2010. In the last years of the studied period, after 2010, a break in the positive trend is observed, as could also be seen from Fig. 1. Thereafter, the environmental share and number of green patents decreases for all countries except GB, where there is a decline only in the last year. The decline is found in both the public and private sectors, with the German public sector as an exception with an increasing number of patents also in the last years.

For the private sector, the scale of R&D had a positive contribution to environmental patent application growth over the whole time period and in all countries except GB. In GB, the impact of the scale of R&D activities varies over time, with a negative impact on patent growth in the beginning of the period, which turned positive from the late 1990's. The efficiency of R&D activities seems to have changed over time. For example, in Germany, it contributes positively to environmental patent growth up until 2006, but then turns negative. A similar pattern is observed for China and France. The US stands out as Δ*Efficiency* is negative in almost all years.

In the public sector, almost all decomposition factors show a positive contribution for the studied time period, indicating a general positive trend. The major difference when comparing the private and the public sector is that Δ*Efficiency* contributes positively in most instances for public sector environmental patent growth.

5.1. Analysis of specific technological topics

This section presents the result for the specific technologies: alternative energy production, energy conservation, agriculture and forestry, and waste management, where the countries patent consistently.[11] When analyzing the technological subsample, the priority variable in equation (4), indicating if the specific technological field has increased in priority over time, can also be calculated.

For the private sector, the results indicate that there have been shifts in priority, see Table 3. Research in agricultural and forestry, and waste management, has decreased over time, and the number of patents has

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[10] Thus, if all decomposition factors are positive, the curve would be located at the top of the stacked bars. If there are both positive and negative factors, the curve is located below the top of the stacked bars.

[11] For example, the two sectors 'Administrative, regulatory or design aspects', and 'Nuclear power' generation, from Table A1 in the Appendix, have very few numbers of triadic patents being filed, making meaningful analysis difficult.

Table 3
Private sector LMDI decomposition result for specific environmental technological topics.

Country	Decomposition Factors 1990–2014				
	Panel A: Alternative Energy Production				
	ΔPriority	ΔEnv. share	ΔEfficiency	ΔScale	Δy
France	22%	15%	−70%	46%	13%
Germany	26%	54%	−80%	53%	53%
GB	7%	72%	−66%	18%	30%
Japan	−13%	128%	−28%	93%	180%
US	−4%	27%	−70%	56%	8%
	Panel B: Agricultural and Forestry				
	ΔPriority	ΔEnv. share	ΔEfficiency	ΔScale	Δy
France	−65%	8%	−38%	25%	−70%
Germany	−57%	35%	−50%	34%	−38%
GB	−80%	38%	−35%	10%	−67%
Japan	−132%	49%	−11%	36%	−57%
US	−18%	25%	−65%	52%	−7%
	Panel C: Energy Conservation				
	ΔPriority	ΔEnv. share	ΔEfficiency	ΔScale	Δy
France	150%	22%	−105%	69%	136%
Germany	271%	98%	−142%	95%	322%
GB	130%	106%	−98%	27%	165%
Japan	159%	193%	−41%	140%	450%
US	109%	40%	−105%	83%	127%
	Panel D: Waste Management				
	ΔPriority	ΔEnv. share	ΔEfficiency	ΔScale	Δy
France	−57%	9%	−42%	28%	−68%
Germany	−32%	41%	−60%	40%	−11%
GB	9%	72%	−67%	19%	33%
Japan	−42%	115%	−25%	83%	131%
US	−38%	22%	−58%	46%	−28%

Table 4
Public sector LMDI decomposition result for specific environmental technological topics.

Country	Decomposition Factors: 1990–2014				
	Panel A: Alternative Energy Production				
	ΔPriority	ΔEnv. Share	ΔEfficiency	ΔScale	Δy
France	43%	77%	152%	46%	317%
Germany	45%	50%	118%	158%	370%
GB	6%	35%	−39%	45%	47%
Japan	63%	−1%	590%	140%	756%
US	−7%	−9%	−20%	43%	7%
	Panel B: Agricultural and Forestry				
	ΔPriority	ΔEnv. share	ΔEfficiency	ΔScale	Δy
France	−25%	63%	125%	38%	200%
Germany	−118%	26%	61%	81%	50%
GB	−77%	20%	−22%	−25%	−54%
Japan	−186%	0%	235%	41%	90%
US	58%	−11%	−26%	55%	76%
	Panel C: Energy Conservation				
	ΔPriority	ΔEnv. share	ΔEfficiency	ΔScale	Δy
France	466%	141%	281%	84%	973%
Germany	229%	69%	163%	218%	679%
GB	281%	68%	−75%	86%	360%
Japan	494%	−1%	951%	167%	1611%
US	482%	−23%	−56%	117%	520%
	Panel D: Waste Management				
	ΔPriority	ΔEnv. share	ΔEfficiency	ΔScale	Δy
France	−127%	33%	65%	20%	−10%
Germany	146%	17%	39%	53%	−37%
GB	−93%	1%	−1%	1%	−92%
Japan	−115%	−1%	380%	67%	332%
US	−63%	−6%	−14%	29%	−53%

Note: Columns correspond to decomposition factors, Δy is change in the left-hand side variable for equation (5), i.e. change in patents.

declined, as indicated by a negative score of Δy. The two technological sectors both have a negative Δ*Priority*, indicating that other environmental research areas have received greater priority. Energy conservation and alternative energy production have increased in almost all countries. For these sectors, positive scores for Δ*Priority* are observed from the LMDI calculation, except for alternative energy production in Japan and US. This indicates that these technological topics have been given a higher research priority, an effect that contributes positively to the growth of environmental patent applications. Similar to the aggregate result, Δ*Efficiency* has a negative score and, thus, a negative impact on environmental patenting over the period. The Δ*Scale* is positive for all countries and technologies, implying that an increased scale of R&D effort has had a positive effect on the growth in environmental patents, even where the total number of patents has decreased.

The relative importance of the variables for developments in the private sector differs across the technological topics. For example, the increase in alternative energy production is driven mainly by the Δ*Env. share* and the Δ*Scale*, whereas, for energy conservation, increased Δ*Priority* appears to be the main driving factor, except for Japan, where the Δ*Env. share* yields a higher score.

The corresponding results for the public sector is shown in Table 4, and turn out to be more diverse. Additionally, the changes in environmental patents are larger in relative terms, although the actual number of patent applications is generally smaller, compared to the private sector. A general increase in environmental patents is observed in all technological topics, except waste management. As could be expected from the result for the public sector in the aggregate case, Δ*Efficiency* has a large positive score and a strong impact on the development of environmental patents. Similarly, the Δ*Env. share* is contributing significantly. Research into energy-related technologies is receiving increased priority, especially in the case of energy conservation. Thus, the priority changes between technologies are similar to those found for the private sector.

There is a considerable variation for the public sectors in different countries with respect to factors of importance for the development in Δy. For Japan, which experienced increases in environmental patents across all technological sectors, Δ*Efficiency* is always the highest contributing factor. France shows a similar pattern, except for energy conservation where Δ*Priority* is more important. Waste management technologies have received less attention over the period, indicated by the negative score of Δ*Priority*, and in all countries except Japan the number of patents has decreased. The result for agricultural and forestry innovation reveal a decreased priority in all countries except the US while simultaneously, the countries have increased the numbers of patents in the field.

When comparing the development across the public and private sector, some observations can be made. Patent applications in environmental technology for forestry and agriculture have increased for the public sector in all countries except GB, while they have decreased in the private sector in all countries. The striking difference is that even though both sectors have seen decreases in priority, the number of patents in the public sector has increased. This implies that other factors are driving the development. In particular, Δ*Env. share* and Δ*Efficiency* contribute significantly and positively for the public sector, see Table 4. Also, for the energy-related technologies patent activity has increased consistently in both sectors; however, there are differences in the decomposition factors. The public sector patent trend in waste management has been negative, except in Japan. The private sector waste management patent trend in Japan and GB is positive, but it is negative for the remaining three countries. For Japan, the public sector result is driven by increases in efficiency, whereas the private sector result is driven by increased general focus on environmental patents and the scale of R&D operations. Graphs over the contributions of the decomposition factors over time for each technological field can be found in Fig. A1–A8 in the Appendix.

6. Discussion

The aim of the paper was to compare trends in environmental patenting between the public and private sectors. We study the development of environmental triadic patents from 1990 to 2014. This time period is of interest because of the increased focus of policy makers on the importance of environmental technology for reaching environmental goals. For example, both the European Union and the US have indicated the importance of new eco-innovation in meeting environmental goals (The White House, 2021; European Commission, 2011). We use an LMDI approach, which allows us to examine the trends in environmental technology patent applications as well as factors determining the development of environmental patenting in the two sectors.

The share of environmental patents of the total patent volume increased for the studied period until 2010 when it started to decline. The increased focus on environmental issues and climate change might explain the increasing patent share until 2010. Concurrently, the stringency of environmental policy increased in the countries included, which is reflected in the OECD Environmental Policy Stringency Index.[12] However, the development in policy stringency in the studied countries stalled between 2011 and 2015, which might explain the declining share of environmental innovations. A possible explanation for the stalled development in policy stringency is the fact that the first commitment period of the Kyoto protocol ended in 2012. As shown by Miyamoto and Takeuchi (2019), the first commitment period led to increased international patent applications for renewable energy technologies, in particular in countries with more ambitious commitments. In the following second commitment period several countries, including Japan, did not take on further binding commitments, and USA did not ratify the agreement, which could have led to reduced incentives for eco-innovation.

Results at aggregate level for the private and public sector, respectively, show differences in the contribution of the efficiency of R&D to patent growth. In the private sector, efficiency decreased and contributed negatively to environmental technology patent growth. This suggests that research output in terms of patents in relation to R&D expenditure has decreased. This is contrary to what could be expected based on the literature: typically, the private sector is favored for R&D due to markets ensuring that firms are more efficient than public agents (Archibugi and Filippetti, 2018; David et al., 2000). However, the private research sector has experienced increased costs for R&D over time (Arora et al., 2018) which reduces efficiency. Additionally, as new technologies successively become more advanced, increased investment is necessary for further technological advancement (Fujii and Managi, 2016; Popp, 2019). The increased efficiency in the public sector could potentially be explained by increased R&D collaborations between the public and private sectors in the studied countries (Ankrah and AL-Tabbaa, 2015; Archibugi and Filippetti, 2018; Lehrer et al., 2009; Motohashi and Muramatsu, 2012). Private entities are filing most of the patents, and, if researchers in the public sector are associated with private sector R&D through collaboration, this could benefit public sector research without large impacts on costs. The reduced efficiency in the private sector could be an important issue for policy makers that rely on environmental innovations to solve environmental problems. However, it should be noted that our results are concerned with relative changes in efficiency and hence, we do not show that the private sector is less efficient than is the public sector in absolute terms.

Across technologies, we observed some differences between public and private sector. For example, in agriculture and forestry, environmental patent growth increased in the public sector, while it decreased in the private sector. Historically, public R&D has been important for innovation in agriculture (Clancy et al., 2016; Fuglie and Toole, 2014; Pardey et al., 2015). This is argued to be because the social benefits from improved technology have generally been high (Clancy et al., 2016), whereas it has been relatively harder to retain the potential profits (Archibugi and Filippetti, 2018). If profits are harder to retain for environmental agricultural and forestry technology, then private firms are not as willing to innovate, as they only get to keep a fraction of the benefits of the R&D (Popp and Newell, 2012). The social benefits of environmental technology have also been suggested to be generally higher than those of conventional technology (Popp and Newell, 2012); if so, this effect could potentially be augmented for the agricultural and forestry R&D. However, our results do not confirm that as both the public and the private sectors show a decreasing priority of agricultural and forestry research. In contrast, patents in alternative energy production have grown for both sectors, driven mainly by increased research priority; in particular for the public sector. A potential explanation is that development of new energy production technologies relies on new findings in 'basic research' (Fujii, 2016), where the public sector plays a larger role. Energy conservation patenting has increased substantially in both sectors, driven by increased priority. This trend could potentially be driven by the increased focus on environmental issues related to energy usage and production, but it may also be driven by increases in energy prices over the period (Fouquet, 2011; van de Ven and Fouquet, 2017). Energy conservation technology is the area in which private patents have increased the most, which might be due to the fact that these technologies are closely related to technological devices necessary for firms to reduce production costs and stay competitive (Fujii and Managi, 2016).

A limitation of our study is that R&D expenditure data does not consider the source of funding, implying that it cannot be said to what extent public funding have contributed to the development of patents in the private sector. Also, as observed by Mowery et al. (2010), public-private partnerships in the USA often grant the intellectual property rights for results from jointly funded research to the private partners. Hence, our results relating to R&D expenditure should be interpreted with this in mind. In line with this, a further limitation is that we do not consider the possibility that public investment and subsidies toward R&D might crowd-out the private sector R&D spending. The results in the literature on this topic are mixed. Görg and Strobl (2007) suggest that small public grants increase private R&D expenditure, whereas larger grants can crowd out private R&D spending for domestic firms, but no corresponding effect was found for foreign firms. Notably, the more recent literature review by Becker (2015) suggests that public subsidies do not crowd out private R&D, which represents a shift in the literature. For example, more solid evidence has been provided that R&D subsidies and tax credits stimulate private R&D in general (Becker, 2015). Hence, the potential issues with crowding-out effects are more complex than only being an effect of increased public spending on R&D. Another limitation is that the framework used does not allow for direct evaluation of specific policies and events during the time period. Also, future studies could potentially carry out more detailed analysis of determinants, especially for the public sector. There are examples where micro-level datasets have been employed for manufacturing firms, successfully identifying determinants of patenting and innovation in the private sector (Horbach, 2008; Horbach et al., 2012; Triguero et al., 2013). However, to our knowledge, the corresponding micro-level information for the public sector does not yet exist. Additionally, the decomposition analysis framework does not account for potential lag effects between investment in R&D and patents. Such lags are relevant, and could be heterogeneous across technological topics (Fujii and Managi, 2016).

7. Conclusions

This study examines patent trends in environmental technologies, decomposed into four determinants in six major innovative countries, and highlights the differences between innovation in the public and private sectors of the economy. The development of environmentally

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[12] https://stats.oecd.org/Index.aspx?DataSetCode=EPS.

sustainable technologies is important for the mitigation of climate change and other environmental issues. Understanding the roles of the public and private sectors is necessary to construct meaningful research policy and environmental policy that supports the development of new environmental technologies. This paper contributes to the literature on eco-innovation and expands on the role of public sector innovation.

The findings indicate that, at an aggregate level, and contrary to what is usually expected in the literature, the main difference between the public and private sector drivers of environmental innovation is efficiency. The public sector has increased the number of patent applications in relation to R&D expenditure, whereas the opposite has occurred in the private sector, implying that public R&D has become relatively more efficient. It is also clear that R&D has shifted in focus and that environmental R&D is increasing, generating more patents over the study period as a whole. Disaggregating into different technological topics, the private and public R&D priorities seem to be moving in the same directions with more energy-related research. We also observe that, for technologies that have a higher potential for generating external social benefits, e.g., agriculture, the public sector has maintained a positive patent growth, whereas in the private sector, a priority shift has occurred to more energy-related technologies. The priority shift was large enough to negatively influence agriculture and forestry patent growth in the private sector. The private sector appears instead to increasingly focus on technologies where profits are easier to retain, in line with the R&D literature. This can be related to the concept of technological paradigms (Dosi, 1982), where such a paradigm is defined by its focus on specific problems that need to be solved, and on specific knowledge related to the solutions. Our results suggests that the technological paradigms differ substantially between the two sectors, with the public sector having a stronger focus on land use sector problems, and the private sector on the energy sector. However, if the decreasing efficiency over time in the private sector innovation continues in a similar manner as during the study period, this could potentially change. One reason for the declining efficiency in the private sector could be that technologies that can be seen as low hanging fruits have already been developed, and more advanced technologies are now researched. Reduced research efficiency in the private sector will then either slow down technological progress, implying that technological progress becomes more expensive, or lead to a shift in private sector research focus to other fields if the economic gains become relatively higher. In either case, this can challenge global aims to address climate change.

The role of the public sector for innovation of environmentally sustainable technologies might become more important in the future. Long-term technological progress is often associated with breakthroughs in basic research (Archibugi and Filippetti, 2018), and the public sector plays an important role in that context (Fujii and Managi, 2016). Policy makers could make sure that the basic research necessary for environmentally sustainable technologies is being pursued, which would also enhance the effect of R&D efforts in the private sector. Our results suggest that firms are conducting research in areas that have received high policy attention, such as energy related topics. The energy related research is also close to the consumer products, and hence it could be easier to anticipate the impact on profits, and to retain the profits. However, policy makers also need to consider where innovation is necessary from an environmental perspective, and facilitate research in these areas. Incentives for firms through environmental and research policy, combined with public research efforts, can accommodate a needed development.

CRediT authorship contribution statement

Tobias Häggmark: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Katarina Elofsson:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Total number of patents over the period 1990–2015.

	Number of patents (% of total patents)	Alternative energy production	Energy conservation	Forestry and agriculture	Waste management	Number of green patents (% of total green patents)	Number of non-green patents (% of- total patents)
Panel A							
Private	946 329 (95%)	71 213 (85%)	22 399 (96%)	15 186 (93%)	19 609 (95%)	139 949 (90%)	806 380 (97%)
Public	45 026 (5%)	12 802 (15%)	906 (4%)	1 226 (7%)	941 (5%)	16 244 (10%)	28 781 (3%)
Total	**991 355**	**84 015**	**23 305**	**16 412**	**20 550**	**156 193**	**835 162**
Panel B							
China - Private	36 791	2 977	294	1 141	494	5 056	31 735
China - Public	661	184	9	10	8	213	448
France – Private	52 287	3 178	815	609	993	6 317	45 970
France - Public	9 019	2 188	209	112	339	3 065	5 954
Germany – Private	129 686	9 628	2 886	3 997	3 263	21 161	108 524
Germany – Public	4 094	946	72	39	58	1 151	2 944
GB – Private	30 624	3 109	494	777	834	5 496	25 128
GB – Public	3 261	846	71	61	72	1 062	2 200
	370 403	25 099	12 069	2 614	8 230	54 434	315 969

(*continued on next page*)

Table A1 (*continued*)

	Number of patents (% of total patents)	Alternative energy production	Energy conservation	Forestry and agriculture	Waste management	Number of green patents (% of total green patents)	Number of non-green patents (% of- total patents)
Japan – Private							
Japan – Public	8 258	2 053	229	136	202	2 668	5 591
US - Private	326 539	27 222	5 841	6 047	5 796	47 485	279 054
US - Public	19 732	6 566	318	867	261	8 086	11 646
Total	**991 355**	**84 015**	**23 305**	**16 412**	**20 550**	**156 193**	**835 162**

Table A2
Overview of technological topics and technology subgroups included in the IPC Green Inventory.

Technological topics	Technology subgroups
Alternative Energy Production	Biofuels
	Integrated gasification combined cycle
	Fuel cells, Pyrolysis or gasification of biomass
	Harnessing energy from manmade waste
	Hydro energy
	Ocean thermal energy conversation
	Wind energy
	Solar energy
	Geothermal energy
	Use of heat not derived from combustion
	Using waste heat
	Devices for producing mechanical power from muscle energy
Transportation	Vehicles in general
	Rail vehicles
	Vehicles other than rail
	Marine vessel propulsion
	Cosmonautic vehicles using solar energy
Energy Conservation	Storage of electrical energy
	Power supply circuitry
	Measurement of electricity consumption
	Storage of thermal energy
	Low energy lightning
	Thermal building insulation in general
	Recovering mechanical energy
Waste Management	Waste disposal
	Treatment of waste
	Consuming waste by combustion
	Reuse of waste material
	Pollution control
Agricultural and Forestry	Forestry techniques
	Alternative irrigation techniques
	Pesticide alternatives
	Soil improvements
Administrative, Regulatory, or Design aspects	Commuting (HOV, teleworking)
	Carbon/emission trading
	Static structure design
Nuclear Power Generation	Nuclear engineering
	Gas turbine power plants using heat source of nuclear origin

Note: Only four of the listed technological topics are analyzed in the specific technology section in the paper; these are alternative energy production, energy conservation, waste management, and agriculture and forestry. For the aggregate section all technological sectors are summed together.

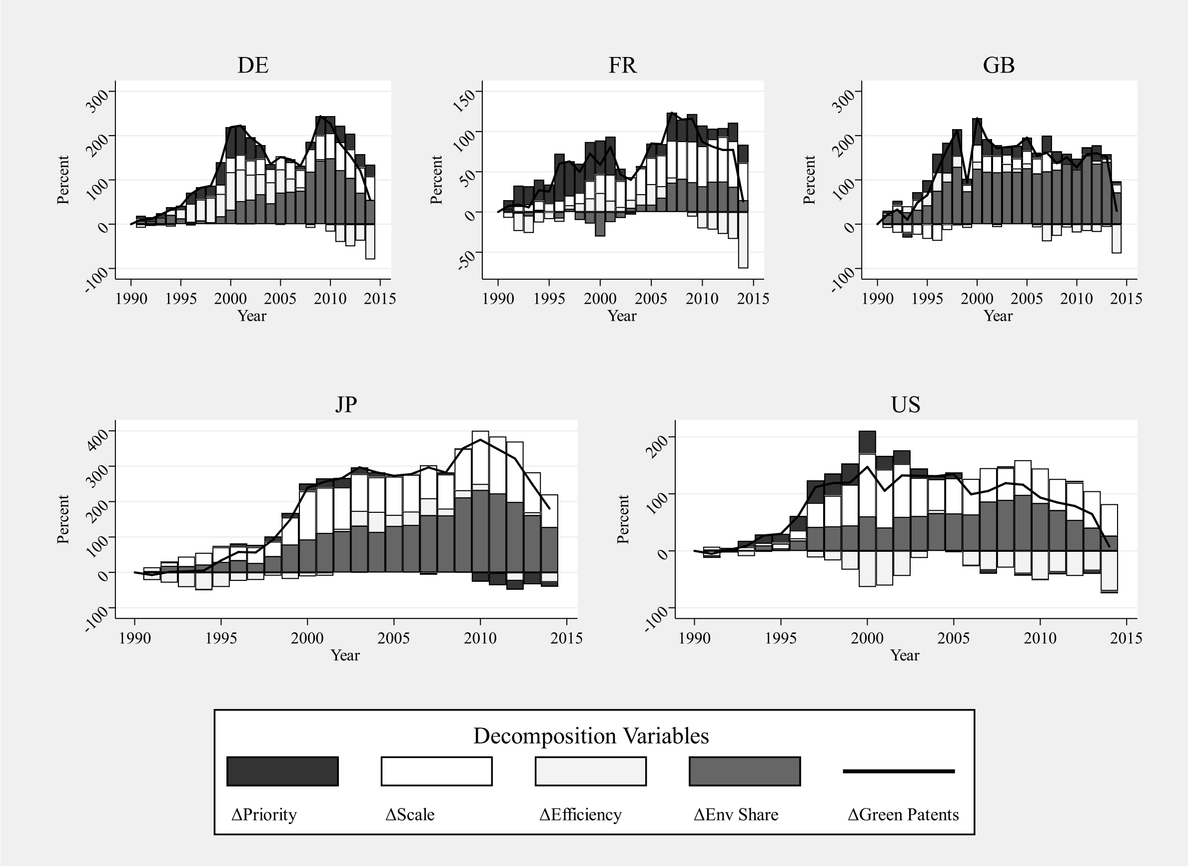

Fig. A1. Private sector, alternative energy production, LMDI decomposition result for 1994–2014.
Note: DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. Y-axis shows percentage indication of how much the decomposition variables affected the change in green patents (*y*).

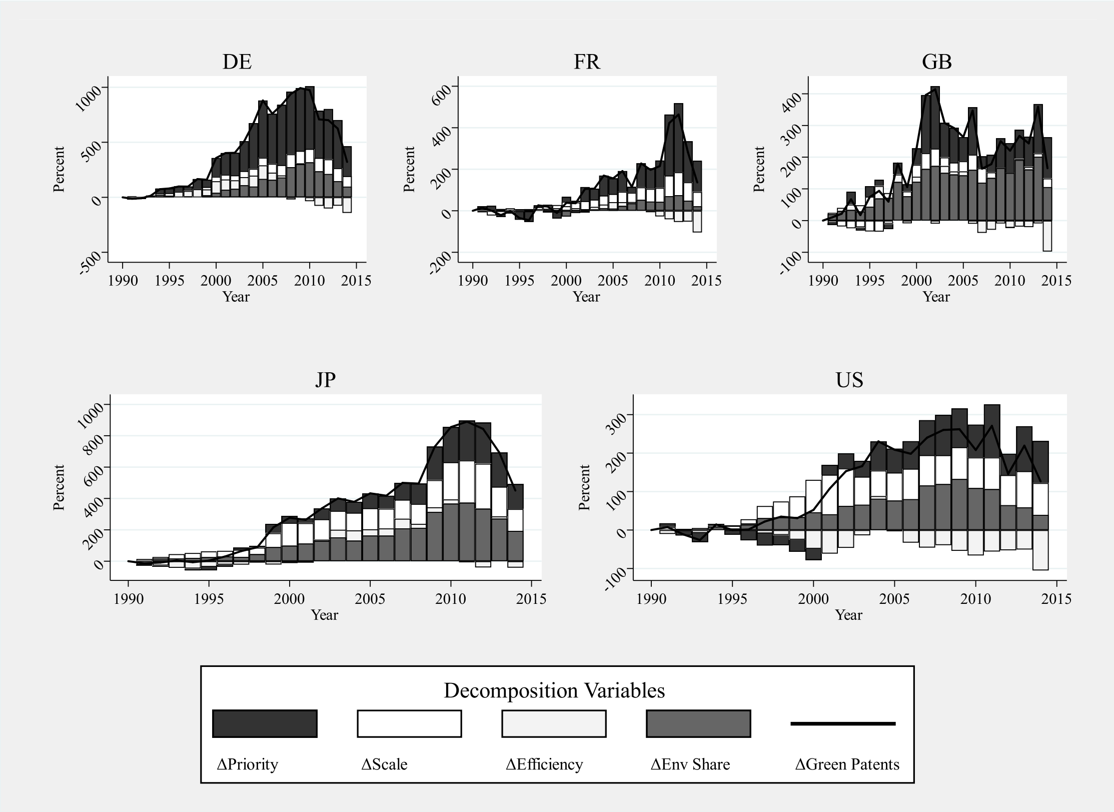

Fig. A2. Private sector, energy conservation LMDI decomposition results for 1994–2014.
Note: DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. Y-axis shows percentage indication of how much the decomposition variables affected the change in green patents (y).

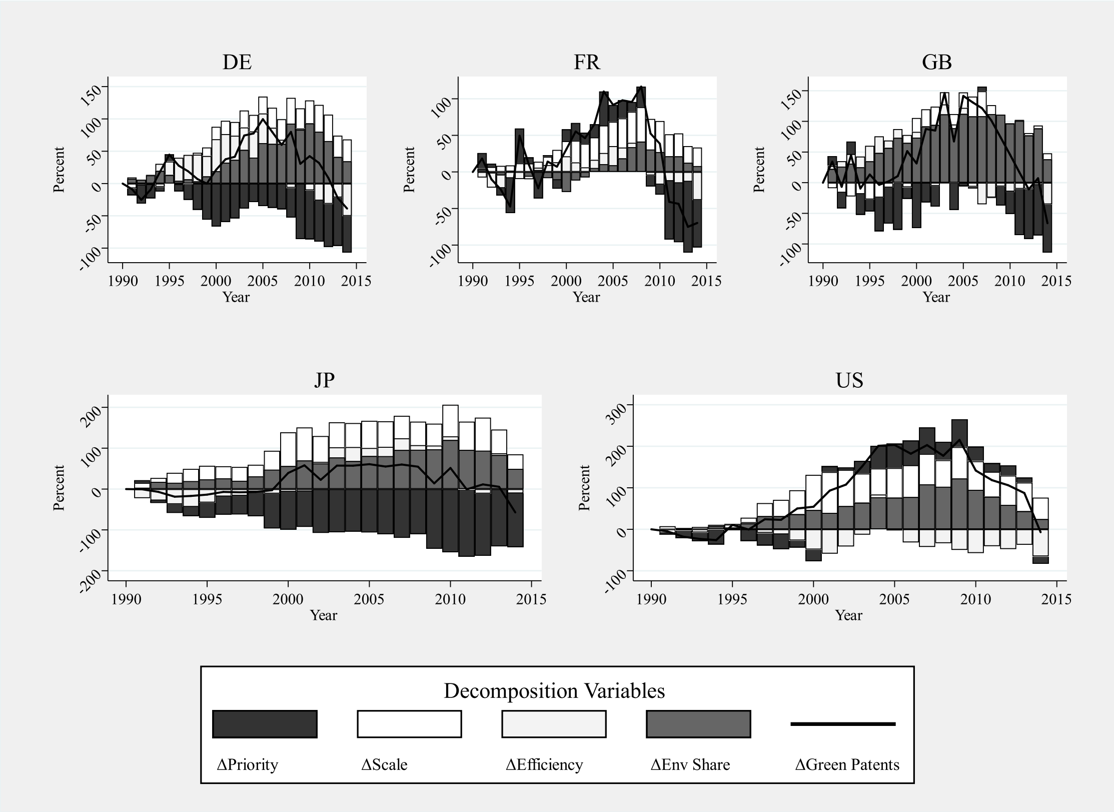

Fig. A3. Private sector, forestry and agriculture LMDI decomposition results for 1994–2014.
Note: DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. Y-axis shows percentage indication of how much the decomposition variables affected the change in green patents (y).

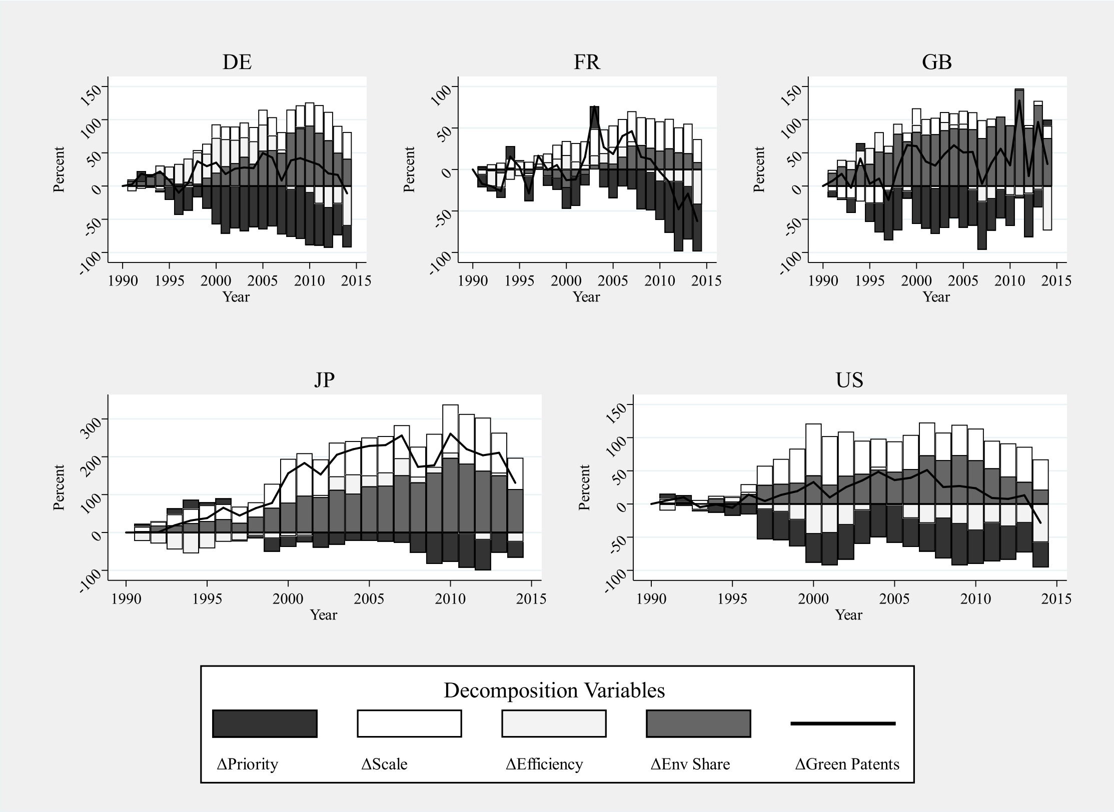

Fig. A4. Private sector, waste management LMDI decomposition result for 1994–2014.
Note: DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. Y-axis shows percentage indication of how much the decomposition variables affected the change in green patents (*y*).

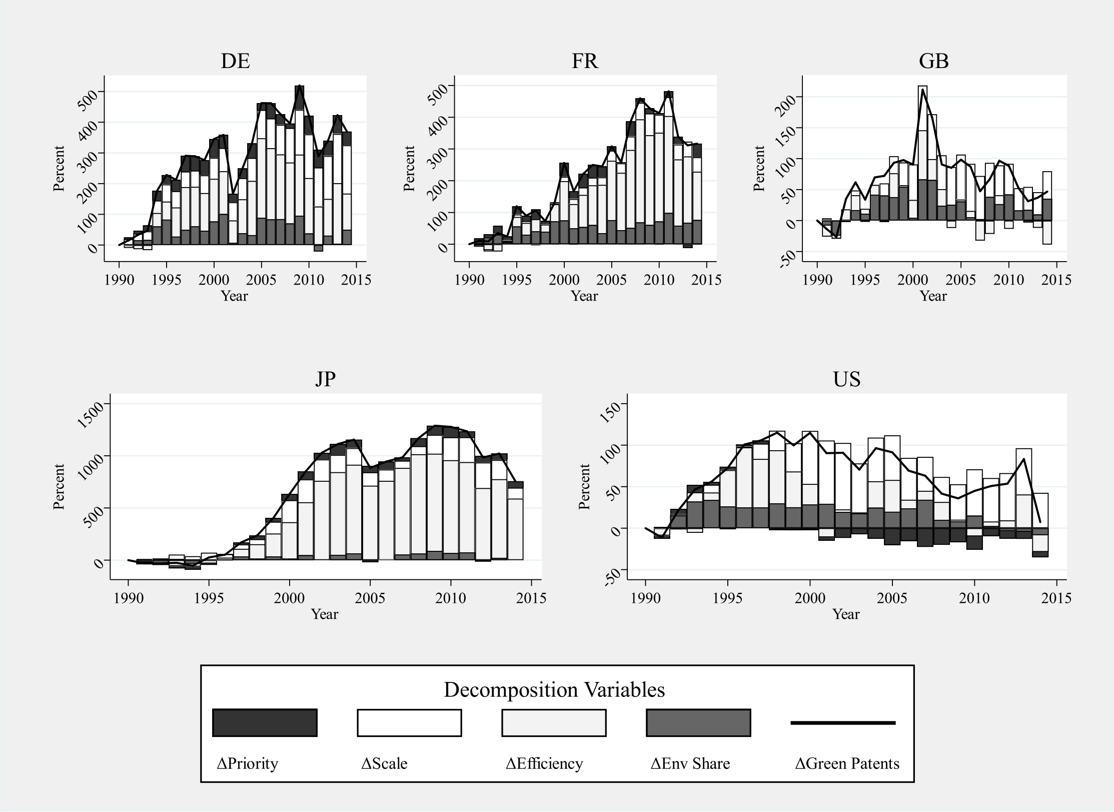

Fig. A5. Public sector, alternative energy production LMDI decomposition result for 1994–2014.
Note: DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. Y-axis shows percentage indication of how much the decomposition variables affected the change in green patents (y).

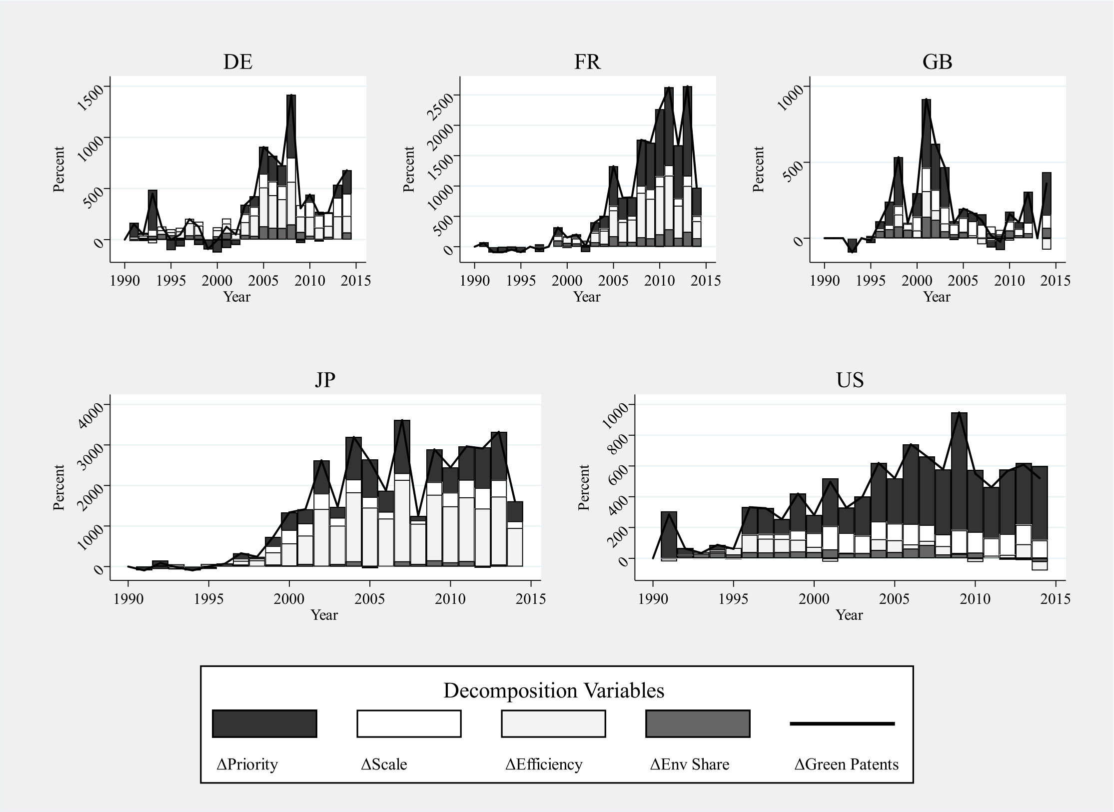

Fig. A6. Public sector, energy conservation LMDI decomposition result for 1994–2014.
Note: DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. Y-axis show percent for indication of how much the decomposition variables affected the change in green patents (*y*).

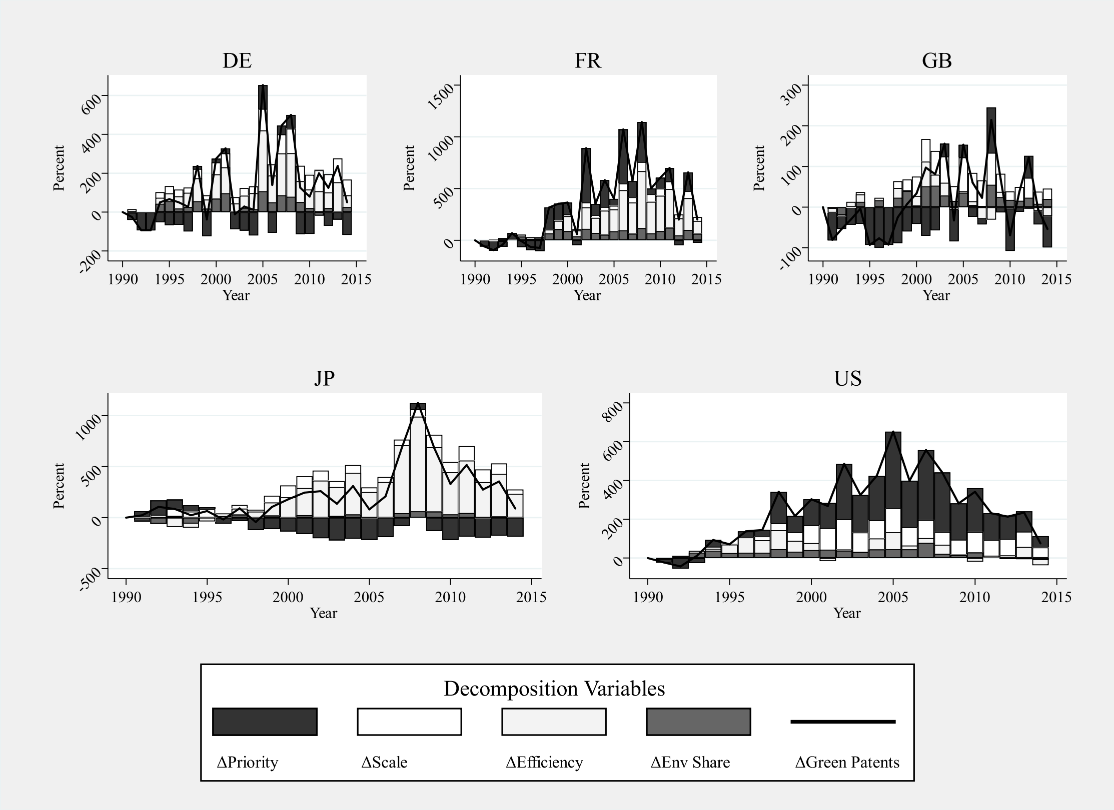

Fig. A7. Public sector, agricultural and forestry LMDI decomposition results for 1994–2014.
Note: DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. Y-axis show percent for indication of how much the decomposition variables affected the change in green patents (*y*).

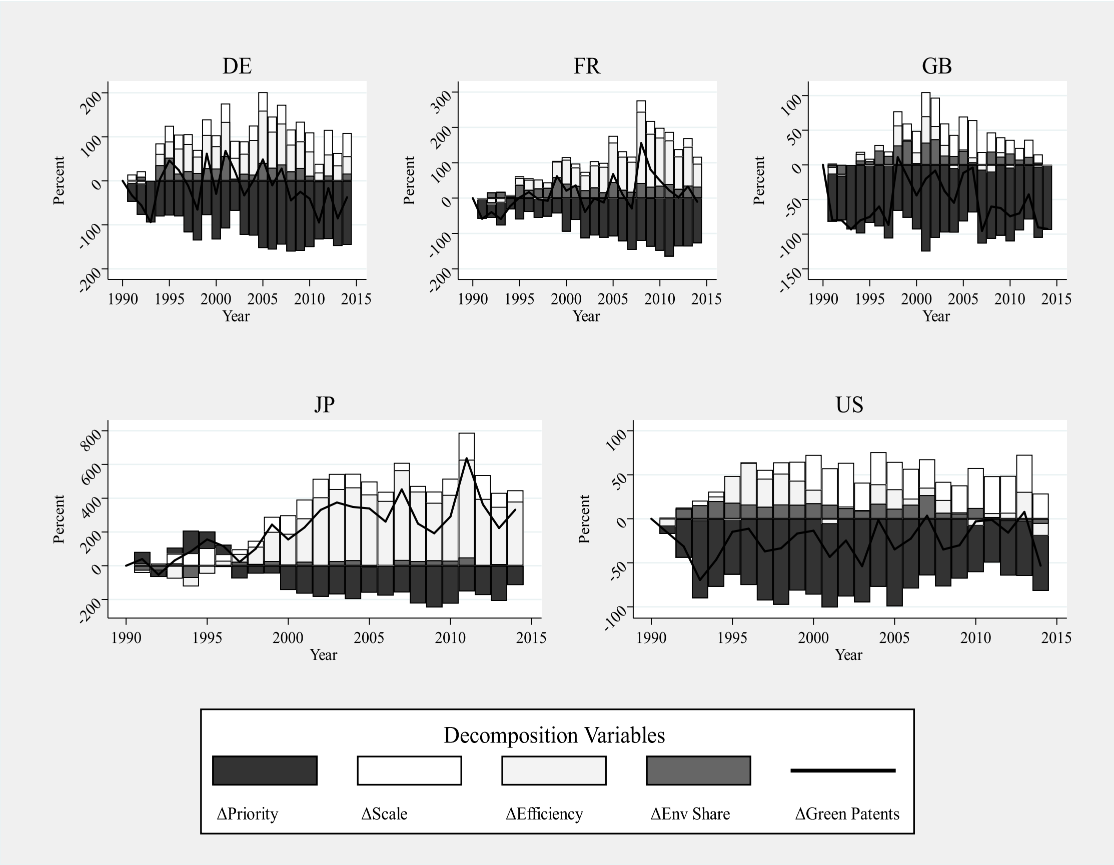

Fig. A8. Public sector, waste management LMDI decomposition results for 1994–2014.
Note: DE = Germany, FR = France, GB = Great Britain, JP = Japan, US = United States. Y-axis show percent for indication of how much the decomposition variables affected the change in green patents (y).

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