

## Article

# Measurements and Trends in Technological Eco-Innovation: Evidence from Environment-Related Patents

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**Abstract:** The concept of eco-innovation addresses a reduction in negative environmental impacts and the more efficient use of resources. As an integral part of eco-innovation, green technologies are receiving increasing attention due to growing environmental concerns. Patent data are one of the measures of the output of technological eco-innovation. However, understanding the patenting of eco-innovation comes with challenges. The aim of this study is to measure the output of eco-innovation and to analyse the trends in green technologies based on environment-related patents in the world's leading countries from 2000 to 2017. For this research, a range of data collection techniques based on patent data from leading countries such as China, Korea, Japan, United States and Germany were employed. The study provides a comprehensive overview of changes and trends in the development of environmental technologies using different domains. In particular, significant progress has been made in the areas of environmental technologies and climate change mitigation technologies related to energy generation, transmission or distribution. These technologies are closely linked to international environmental policies such as climate change mitigation and green industry transformation. The study also contributes to the literature on measuring the output of eco-innovation.

**Keywords:** eco-innovation; technological eco-innovation; environmental technologies; patents; sustainability



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## 1. Introduction

The ongoing debate concerning sustainable pathways to economic development has directed the interest of many economists towards a particular type of innovation that is able to conserve environmental resources. Innovation, and by extension eco-innovation, can affect sustainability in many different ways, both positively and negatively [1,2]. Since the Brundtland Report in 1987, a broad debate on eco-innovation and sustainability-oriented innovation has been launched, including the integration of environmental and social aspects into products, processes and organisational structures [3,4]. Thus, eco-innovation supports the implementation of the Sustainable Development Goals (SDGs) focused on the economic, social and environmental dimensions [5–8]. In the context of developing and implementing eco-innovation, both economic and social impact can be demonstrated [5,6,9]. However, in spite of the importance of eco-innovation in the economic debate on environmental sustainability, its meaning still seems unclear [10]. The literature lacks comprehensive theories on eco-innovation.

Eco-innovation therefore emphasises the direction and content of change, considering the environmental dimension of innovation. Green innovation is a type of innovation that can not only have benefits for consumers and businesses but can also significantly reduce negative environmental impact [11,12]. The development of eco-innovation leads to economic growth and the transformation of the economy towards a low-carbon or

circular economy [13–16]. Furthermore, eco-innovations include technological innovations in energy conservation, pollution prevention, waste recycling, green product design and environmental management [7,14–17]. The emergence of eco-innovation aims to decrease dependence on natural fossil resources and reduce the release of harmful substances throughout the life cycle [18]. However, two significant barriers to implementing eco-innovation need to be overcome. These are market uncertainty and an uncertain return on investment [7,12,17,19]. The concept of eco-innovation can be considered as a response developed to address the environmental impacts of economic processes, including changes in technologies [20].

As an integral part of innovation, green technologies are receiving increasing attention due to growing environmental concerns [10,21]. Innovation in green technologies can provide a double dividend: reducing the burden on the environment while contributing to the technological modernisation of the economy [22]. Green technologies contribute to balancing environmental protection and economic development, which is critical to creating a sustainable society [23]. It has been widely recognised that far-reaching innovations are needed to tackle climate change and other environmental challenges. Green technologies include biotechnology and nanotechnology, information and communication technologies, and environmental technologies [24]. Due to the growing importance of green technologies globally, this paper focused on environment-related technologies, including environmental management technologies, water-related adaptation technologies and climate change mitigation technologies. Sustainable green technologies are important in order to control emissions.

A comprehensive methodology for measuring innovation in environment-related technologies was developed by the Organisation for Economic Co-operation and Development (OECD). The OECD indicators allow for the assessment of environment-related innovation in a wider range of countries and cover a greater variety of relevant technologies. The indicators include: a technology development index (a measure of inventive activity) in more than 80 specific environmental technologies, an index of international cooperation in technology development (a measure of co-invention) and a technology diffusion index (a measure of market protection) [25]. These indicators are based on patent data that are widely available, quantitative, commensurate, product-oriented and can be disaggregated, which is a particularly important advantage when analysing environmental technologies. Patent data are one of the measures of green innovation [23,25,26]. Patent data are often used as a measure of technological innovation because the data focus on the results of the inventive process [25]. These data provide a wealth of information about the nature of the invention, the inventors and the applicant. Nevertheless, not all innovations or inventions are patented, and simply measuring the number of patents does not indicate their relative importance or impact. Understanding the patenting of eco-innovation comes with its own challenges. However, the topic is attracting the attention of policymakers and business actors due to its market potential and global concerns.

The aim of this paper was to measure the output of technological eco-innovation and to analyse the trends in green technologies based on environment-related patents in the world's leading countries from 2000 to 2017. The key research question was twofold: (1) how can the output of technological eco-innovations be measured; and (2) how does the development of eco-innovation based on environmental patents in green technologies evolve? The method used was a comparative analysis of the world's five leading countries in patenting: United States, Germany, China, Japan and South Korea. Based on patent data from the OECD, the analysis provides a comprehensive overview of changes in the development of environmental technologies in the selected countries.

This study contributes to the literature on the measuring the output of eco-innovation by analysing the progress of the world's most advanced economies in developing environmental technologies. Using a patent-based approach, the study supports the debate on international market competitiveness of environmental technologies as well as on the development of eco-innovation policy research [27].

The article is organised as follows: The next section defines eco-innovation, focusing on environmental technologies and patent-leading economies. Section 3 deals with the research methodology including the data collection and data analysis methods. Afterwards, the results of the research analysis are presented, focusing on the technological progress required to achieve environmentally sustainable pathways based on indicators for patented environmental technologies. Section 5 presents a general discussion comparing and identifying their contribution to the eco-innovation analysis and sustainable development. The final section provides some concluding remarks and directions for future research.

## 2. Literature Review

### 2.1. The Concept of Eco-Innovation

When analysing changes in the global economy in the face of constant technological progress, counteracting climate change, dwindling resources and striving for a low-carbon economy, the increasing importance of eco-innovation is emphasised [13]. The concept of eco-innovation has been addressed by researchers in various disciplines such as economics [28], sociology [29] and management [30]; and even in the dimensions of design, governance, users and supply chain [31]. Nowadays, the term is used as a synonym for ecological innovation, environmental innovation, green innovation, sustainable innovation, sustainability-driven innovation, sustainability-enhancing innovation and sustainability-oriented innovation [32,33], and includes different technologies (e.g., solar or wind energy systems), organisational practices (e.g., pollution prevention) and services (e.g., electric roads).

One of the first definitions of eco-innovation was proposed by Fussler and James [34] who considered eco-innovation to be the manufacture of new products and processes that provide customer and business value but significantly reduce environmental impacts. Other authors have developed different definitions of eco-innovation. The OECD's (2008) definition emphasises that eco-innovation "... leads to a new or significantly improved product (good or service), process, organisational method or marketing method creating environmental benefits, and that such environmental benefits can occur during the production of goods or services, or during the aftersales use of a good or service by the end users" [35]. A broader definition has been developed by Klemmer et al. [36] and Horbach et al. [22]. They point out that eco-innovation should include process, product and organisational changes in company management, as well as changes at the social and political level, consumer behaviour and lifestyle in general.

According to Hojnik and Ruzzier [37] eco-innovations can be viewed in three dimensions: technological, organisational or institutional. Based on the bibliometric analyses from the Web of Science Core Collection data, Türkeli and Kemp [38] examined more comprehensive perspectives on eco-innovation. These were (1) supply-side perspectives focusing on companies and industries (e.g., drivers and barriers to eco-innovation); (2) technology-focused research (e.g., carbon capture and storage, electric vehicles, smart plugs); (3) academic research (e.g., new materials); (4) sectoral research (e.g., metallurgy and ironmaking, transport, information technology, food, agriculture, tourism); (5) knowledge support component of eco-innovation (e.g., skills and training); (6) demand-side analysis (e.g., diffusion and adoption dynamics of individuals, households, firms); and (7) policy impact perspective (impact of policy instruments, e.g., ecolabels, policy mixes). Türkeli and Kemp [38] considered eco-innovation as entirely new or modified products, processes, techniques or systems that avoid or reduce environmental damage but retain the same use value.

Environmental innovations differ from other innovations owing to the political dimensions underlying their emergence. Eco-innovations, in particular renewable energy technologies, require political support and have a global market potential based on global concerns and discourse about inevitable global warming. Eco-innovation cannot be treated the same as other innovations (e.g., in terms of double externalities and regulatory push/pull

effects), and a specific theory and policy are needed [28]. However, the literature lacks comprehensive theories on eco-innovation [12,24,32].

The role of eco-innovation can be considered within two opposing theoretical perspectives: neoclassical versus evolutionary [10,22,36]. In the neoclassical approach, eco-innovations play a key role in achieving the goal of environmental sustainability, mainly through their contribution to technological progress that can offset the negative effects of natural resource depletion. Hazarika and Zhang [39] point out that factors such as social and economic changes, institutions and policy instruments play an important role in neoclassical theory. They stimulate the development and implementation of eco-innovation. Whereas evolutionists analyse ecological innovation in its dynamic and multidimensional nature, recognising the important role played by organisational, social and institutional innovations for environmental sustainability. In this context, a deterministic neoclassical perspective appears particularly useful for studying the specific features of ecological innovation. Evolutionary theories, on the other hand, are suitable for studying radical innovation and avoiding any technological bias, emphasising the need to take into account social and institutional dimensions. While both approaches recognise the important role of eco-innovation in supporting environmental sustainability, they differ on how eco-innovation can lead economies towards sustainability [10,22]. Given the research objective of this article, the neoclassical approach, which assumes that technological eco-innovation is the main tool for achieving environmental sustainability pathways, seems particularly relevant for further analysis. Nevertheless, the evolutionary approach extends the analysis of eco-innovation to include social and institutional aspects along with technology.

The differences among the types of eco-innovation are not clear; moreover, the development of divergent types of eco-innovation proceeds together. The economic, social and institutional elements interact with each other. One of the most important factors to consider are regulations that affect not only the ecological aspect. Regulations can also contribute to the development of social innovation and institutional innovation, which is extremely important in the context of striving to achieve a model of sustainable development [28]. This requires institutional change, combined with adequate enforcement of regulations that support a sustainable transition [40]. Moreover, social innovations and institutional innovations accompany technological eco-innovations, which are related to their more effective adaptation. Eco-innovation is prone to many disruptions, including decision-making processes, technological progress or the perception of eco-innovation. Hence, it is necessary to take a broader look at the issue of eco-innovation [39].

## *2.2. Measuring the Output of Eco-Innovation by Environment-Related Patents*

The transition towards a sustainable economy, as well as striving to achieve a low-emission economy, requires the implementation of radical solutions, including in the field of technology, which increases the need to develop technological eco-innovations [41]. Technological eco-innovations are necessary to reduce the progressive degradation of the environment and provide a remedy for existing problems, such as the need to remove air pollutants. This requires the optimisation of production processes and the integration of individual components used at the production stage [28,42]. Technological eco-innovations contribute to an increase in resource efficiency, which appears extremely important in the face of dwindling resources, another challenge for the global economy [42,43]. Moreover, technological eco-innovations ensure a less harmful impact on the environment, and the benefits of their implementation include not only individual entities, but also the economy and society as a whole [12,22,44].

Given the technological developments, including registered eco-innovations, patents are growing in importance. Interestingly, this change does not only apply to developed countries. As a result of dynamic economic growth, building a competitive advantage and innovation, the increase in patents is noticeable in emerging economies, especially in China and the South Korea [45]. Despite the fact that, in 2019, the number of patent applications on a global scale fell by 3%, simultaneously 1.4 million applications were submitted to the

National Intellectual Property Administration of the People's Republic of China (CNIPA). It is worth adding that the participation of the CNIPA among the five largest patent offices, such as the United States Patent and Trademark Office (USPTO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO) and the European Patent Office (EPO), has grown constantly from 17% in 2009 to 43.4% in 2019 [45]. As defined by the World Intellectual Property Organization (2020, p. 230), a patent is "a set of exclusive rights granted by law to applicants for inventions that are new, non-obvious and commercially applicable". In order to acquire a patent, technical information about the invention must be disclosed to the public in a patent application [45]. Albino et al. [5] divide the indicators for measuring innovation into two areas: (1) input-based indicators measuring the inputs of innovation processes (e.g., expenditure on R&D) and (2) output-based indicators that test the results of innovation activities (e.g., patents).

Patents are also used to measure eco-innovation due to the availability of data published for long-time series. This allows a detailed comparative analysis or research to be carried out. Moreover, patent data can be a comprehensive source of eco-innovation data as the patent descriptions contain technological information. However, not all eco-innovations are patented. Patents cover only new innovations on the market, including eco-innovations.

In the literature, there are different eco-innovation studies based on patent data [25,46,47]. The studies on patent analysis relate mostly to the leading countries, the main indicators of technological development and the main actors operating in this field. The existing literature shows an increasing trend of patenting of different environmental technologies [48]. The USA and Japan are by far the most dominant countries in the area of waste heat recovery, although their relative share of patent applications is declining [48]. Fujii and Managi [49] examined different determinants of environmental technology inventions in Japan, which is useful in formulating effective policies to promote environmental innovation. The data included seven types of patent technologies in Japan from 2001 to 2010. By using data from patent applications in a decomposition analysis, they found that the number of environmental patent applications increased according to the priority of environmental patents by private firms and in line with improvement in the efficiency of patent applications in the public sector. Moreover, the number of patent applications related to emissions trading increased sharply among private companies, chiefly due to their higher level of priority after 2005.

Walz et al. [47] analysed the dynamics of innovation in green energy and resource efficiency, as well as the position of the Global North and emerging economies. The analysis covered Japan, South Korea, China, EU Member States, United States, Mexico, Australia, Argentina, Turkey and others on the basis of various indicators, including patents. Concerning patents, the following indicators were analysed: dynamics of publications and patents, development of shares of the North and newly industrializing countries in green technology publications and patents, world green export shares and export to GDP ratio of country samples in green technology patents, and the development of patent specialisation of country samples in green technology patents.

In addition to studies on single countries or on many different countries, there are also sector-specific studies in the literature. A study by Carlos Santos Silva et al. [50] based on nine countries (i.e., United States, China, Russia, Germany, Spain, Australia, Canada, Great Britain and Taiwan) concerned the automotive sector (hybrid cars). The study was conducted using the Derwent Innovations Index patent base from the Web of Science. It showed that the United States leads the ranking in green technologies and patents for hybrid cars. However, countries such as Japan, China and Germany have presented significant growth.

Despite the increasing research in the field of eco-innovation and environmental technologies based on patent data, the analyses are often focused on individual countries [46] or industries [50]. Moreover, the existing literature shows that most studies concern the EU and the United States [49]. However, this research can be constantly developed to show the dynamic changes occurring in this field. Given increased mass production and increased

efficiency of technologies, eco-innovations are becoming beneficial to various markets. Therefore, there is a need for a broader approach to the analysis, taking into account leading economies in terms of patents. This article attempts to reveal the progress made in patenting eco-innovations using examples of environmental technologies in the world's leading economies in the field of patents. A comparative analysis of several countries was considered to be a more comprehensive approach, as it will help to assess the progress of ongoing changes in the implementation of environmental technologies. Thus, this gap provides the basis for further research that will extend existing work. Section 3 describes, with sufficient details, the material and methods, which should allow others to replicate and build on the published results.

### 3. Data Sources and Research Methodology

This study focused on eco-innovations by analysing the progress of the world's most advanced economies in developing environmental technologies on the basis of patent-based measurement. Five of the world's leading countries in patenting were chosen for the analysis: United States, Germany, China, Japan and South Korea. These countries were selected based on the newest report by the World Intellectual Property Organization [45]. The data used in the study were mainly drawn from the technology development dataset in the OECD Environment database and the World Bank database. The OECD Directorate for the Environment, in collaboration with the Directorate for Science, Technology and Innovation, has developed patent-based innovation indicators relevant to environmental technology development [25]. These indicators enable the assessment of the innovation performance of countries and companies, as well as the design of government environmental and innovation policies.

The OECD indicators are grouped into three categories: technology development (a measure of inventive activity), international cooperation in technology development (a measure of co-creation) and technology diffusion (a market protection measure) [25]. These indicators provide a range of tools for assessing innovation performance in national and policy research.

This research examined the OECD indicators related to patents on environment technologies. The number of applications on environment-related patents by the priority date under the Patent Cooperation Treaty (PCT) was the main variable covered by the research objectives. To identify trends in environment-related technologies with regard to technology, economic and demographic development dynamics, the following indicators were constructed:

- The share of environment-related patents in the total number of patent applications;
- The number of environment-related patents per million residents;
- The number of environment-related patents per USD 100 billion;
- The distribution of environment-related patents per green technology categories.

The selection of these indicators resulted from the growing importance of the development of green technologies that are closely linked to environmental policies, e.g., in the field of climate change mitigation and the green transformation of industry.

Our research referred to the period between 2000 and 2017. The choice of this time frame was determined, first, by the research objective, which concerned the analysis of eco-innovation output based on environmental patents in the long term, and, secondly, by the availability of comparable data. The particular databases providing useful information on the variables required to calculate the aforementioned indicators are described in Table 1.

**Table 1.** The set of variables analysed.

Indicator	Variable	Data Sources
(1) The proportion of environment-related patents over overall patent applications	Application of environment-related technologies by the priority deadline under the PCT	OECD. Patents in environment-related technologies
	Application in patents by the priority deadline under the PCT	OECD. Patents in environment-related technologies
(2) The number of environment-related patents per million residents	Application of environment-related technologies by the priority deadline under the PCT	OECD. Patents in environment-related technologies
	Population	OECD Statistics
(3) The number of environment-related patents per USD 100 billion	Application of environment-related technologies by the priority deadline under the PCT	OECD. Patents in environment-related technologies
	Gross domestic product (constant, PPP, 2015 reference value)	OECD Statistics
(4) The distribution of environment-related patents per green technology category	Application of environment-related technologies by the priority deadline under the PCT	OECD. Patents in environment-related technologies

Source: own study.

The last indicator covers the following types of technologies:

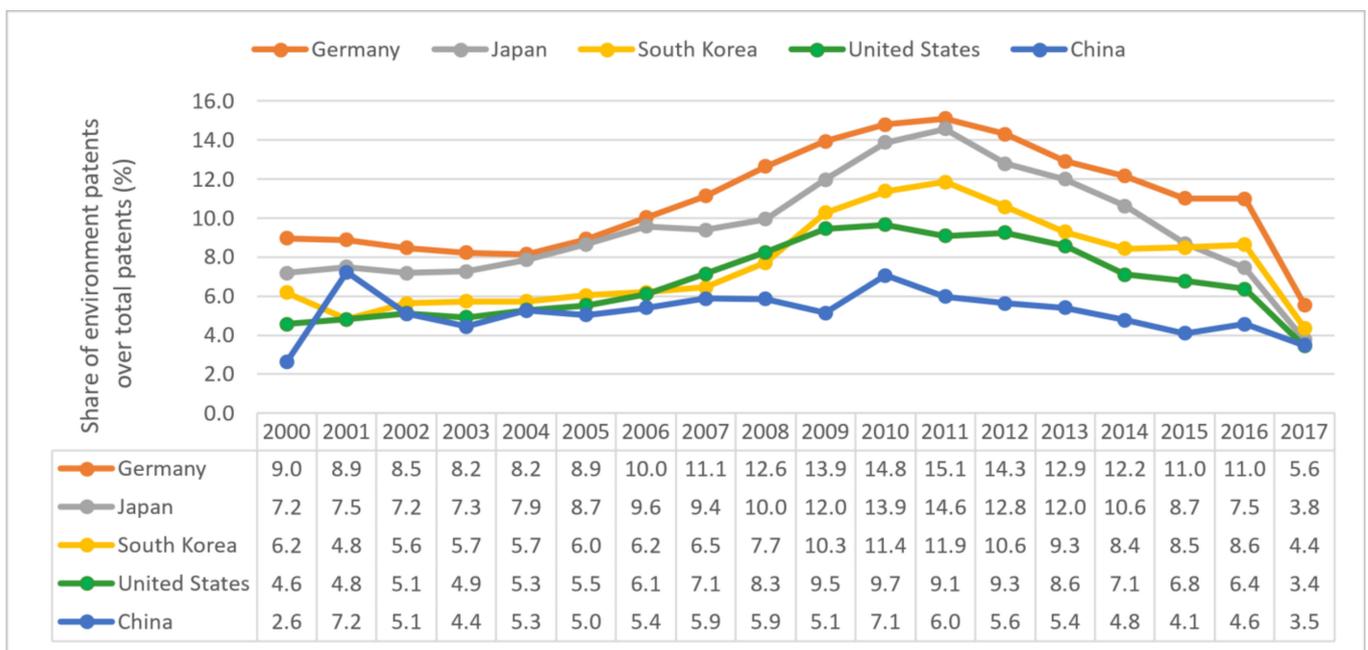
- Water-related adaptation technologies
- Environmental management (including air pollution abatement, water pollution abatement, waste management, soil remediation, and environmental monitoring);
- Climate change mitigation technologies related to wastewater treatment or waste management;
- Climate change mitigation technologies related to transportation;
- Climate change mitigation technologies related to energy generation, transmission or distribution;
- Climate change mitigation technologies related to buildings;
- Climate change mitigation technologies in the production or processing of goods;
- Capture, storage, sequestration or disposal of greenhouse gases.

For environment-related technologies, a comparative analysis method was employed to examine development over the last 17 years. By using a patent-based approach, the study offers a quantitative perspective on current developments in environmental technology, provides indicators of future trends and contributes to the debate on technological competition in the eco-innovation field. Based on patent data from the OECD, the analysis provides a comprehensive overview of changes in the development of environmental technologies in selected countries.

#### 4. Results

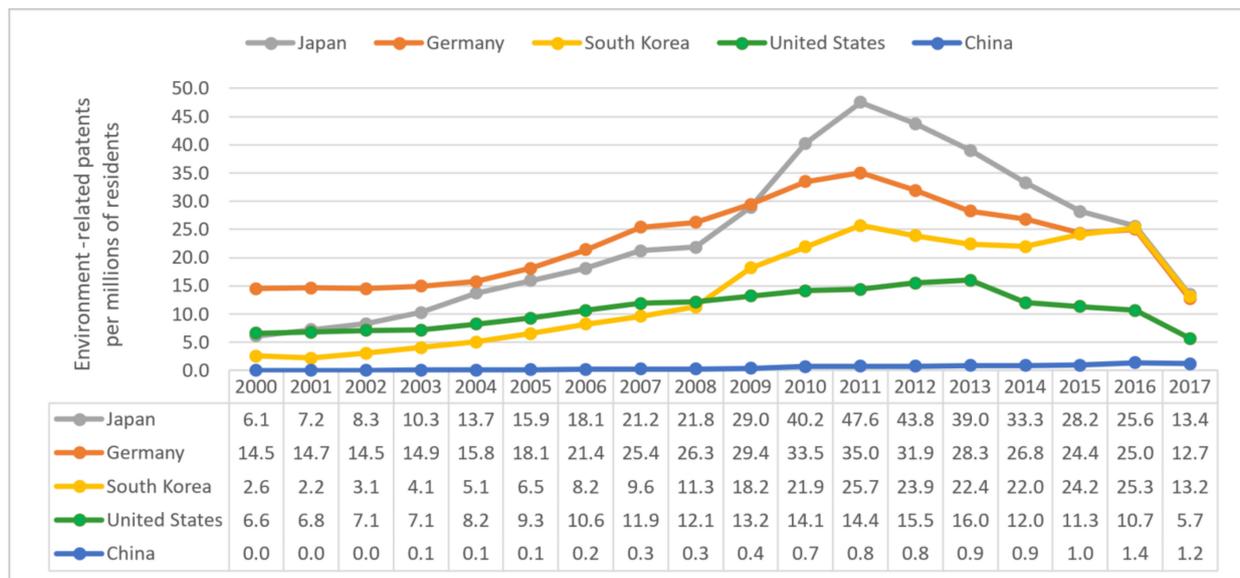
This research focused on the analysis of differences and similarities in the development of environmental technologies in the leading patenting countries in the world based on four indicators: (1) the share of environment-related patents in the total number of patent applications, (2) the number of environment-related patents per million residents, (3) the number of environment-related patents per USD 100 billion, and (4) the distribution of environment-related patents per green technology domains. Based on the analysis of these indicators it was possible to answer the question: how does the development of eco-innovation based on environmental patents in green technologies evolve?

The analysis showed different results in the investigated countries regarding the number of patents on environmental technologies. Given the share of environmental patents in the total number of patents over the years 2000–2017 in the investigated economies, the findings indicated a downward trend. An upward trend continued during the years 2000–2011, while later the share of the number of environmental patents in the total number of patents began to decrease significantly. In 2017, the highest number of environmental patents was recorded in Germany, Japan and South Korea (Figure 1). The rise in the number of environment-related patents in the years 2000–2011 was influenced by such factors as counteracting global warming and improving living standards, as well as growing environmental awareness. It was indicated that these reasons created the need to develop and implement eco-innovations, including technological eco-innovations, which led to an increase in patent applications.



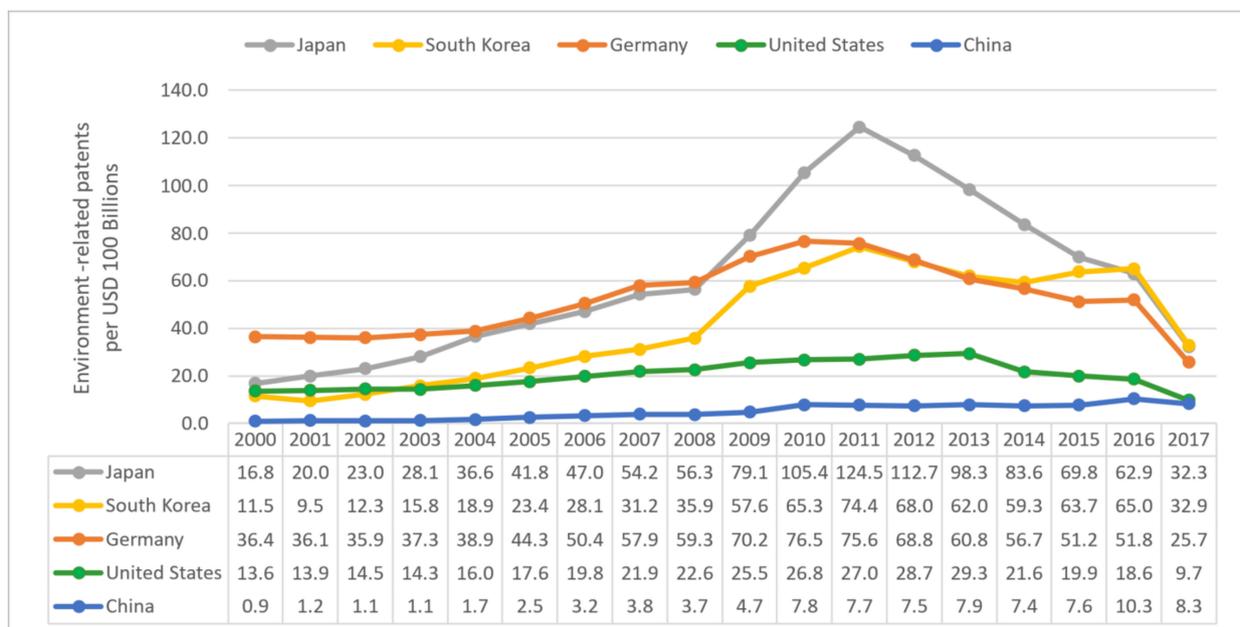
**Figure 1.** Share of environment-related patent applications in the total number of patents from 2000 to 2017 (in %). Source: own study based on OECD (2021), “Patents in environment-related technologies: Technology indicators”, OECD Environment Statistics (database), <https://doi.org/10.1787/e478bcd5-en> (accessed on 24 January 2021).

In the case of patent applications per million inhabitants in the years 2000–2017, a downward trend can also be seen, as was in the share of environment-related patent applications in the total number of patents. The number of patent applications per million inhabitants in China, Germany, Japan, the Republic of Korea and the United States grew until 2011 and, subsequently, began to gradually decline. The largest number of patent applications per million inhabitants in 2017 took place in Germany, Japan and the Republic of Korea (Figure 2). At the same time, in the years 2016–2017, the fall in the number of patents per million inhabitants in these three countries was much more pronounced than in China and the United States.



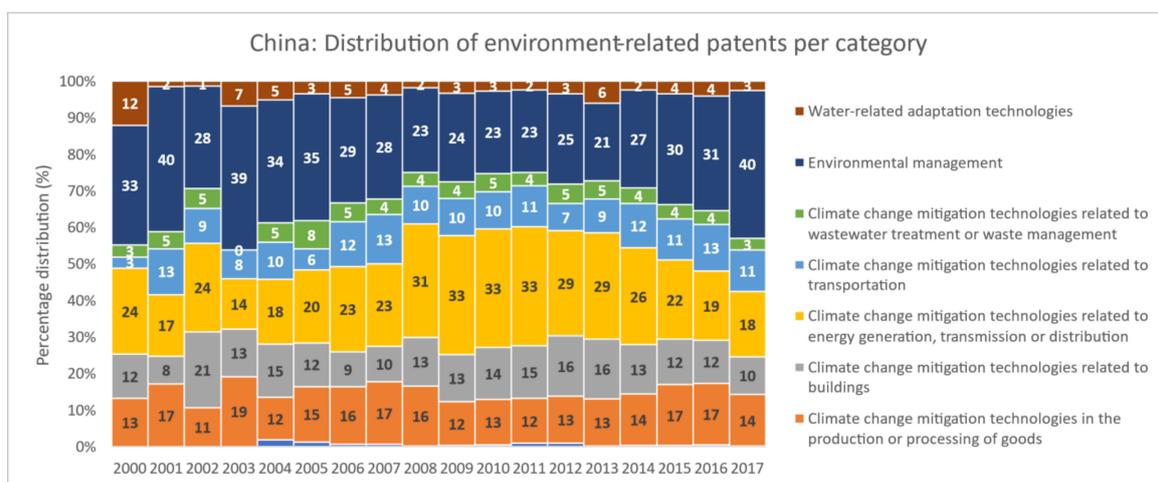
**Figure 2.** Environment-related patent applications per one million residents from 2000 to 2017. Source: own study based on OECD (2021), “Patents in environment-related technologies: Technology indicators”, OECD Environment Statistics (database), <https://doi.org/10.1787/e478bcd5-en> (accessed on 24 January 2021).

A similar downward trend over the analysed period can be observed in the case of patent applications worth USD 100 billion of GDP (Figure 3). In the years 2000–2011, the number of patent applications grew, and after 2011 it began to gradually decline. The largest drop in patent applications, at USD 100 billion of GDP, occurred in Japan, especially in 2011.

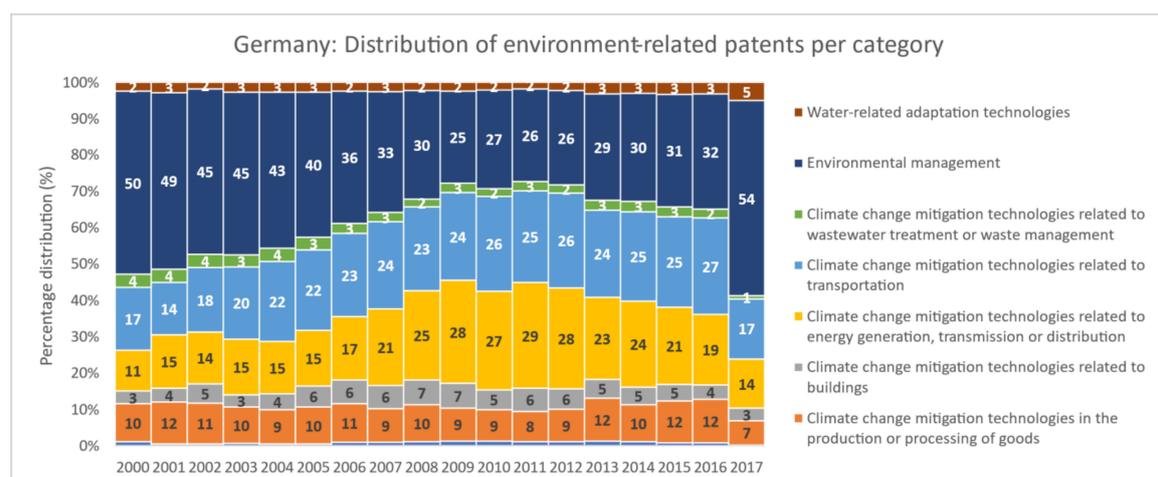


**Figure 3.** Environment-related patent applications per USD 100 billion GDP from 2000 to 2017. GDP was measured in constant prices and purchasing parity terms with 2015 as the reference year. Source: own study based on OECD (2021), “Patents in environment-related technologies: Technology indicators”, OECD Environment Statistics (database), <https://doi.org/10.1787/e478bcd5-en> (accessed on 24 January 2021).

In order to assess the extent to which these countries indicate a shift towards sustainability through technological eco-innovation, it was necessary to analyse the different technology domains. Based on the analysis of the percentage distribution of environment-related patents related to different technology domains, it can be stated that patents in the field of environmental management and climate change mitigation technologies related to energy generation, transmission or distribution dominated in the selected countries recently. In 2017, the share of environmental management patents in the percentage distribution of environmental patents in the examined countries amounted to approximately 50%. Only in China was the share of this category lower, totalling 40% (Figure 4). In turn, the climate change mitigation technologies related to energy generation, transmission or distribution as well as climate change mitigation technologies related to transportation came second and third, respectively, for the analysed countries. The exception was Germany, where the share of climate change mitigation technologies related to transportation accounted for 17% in 2017, compared to 14% of the share of climate change mitigation technologies related to energy generation, transmission or distribution (Figure 5).

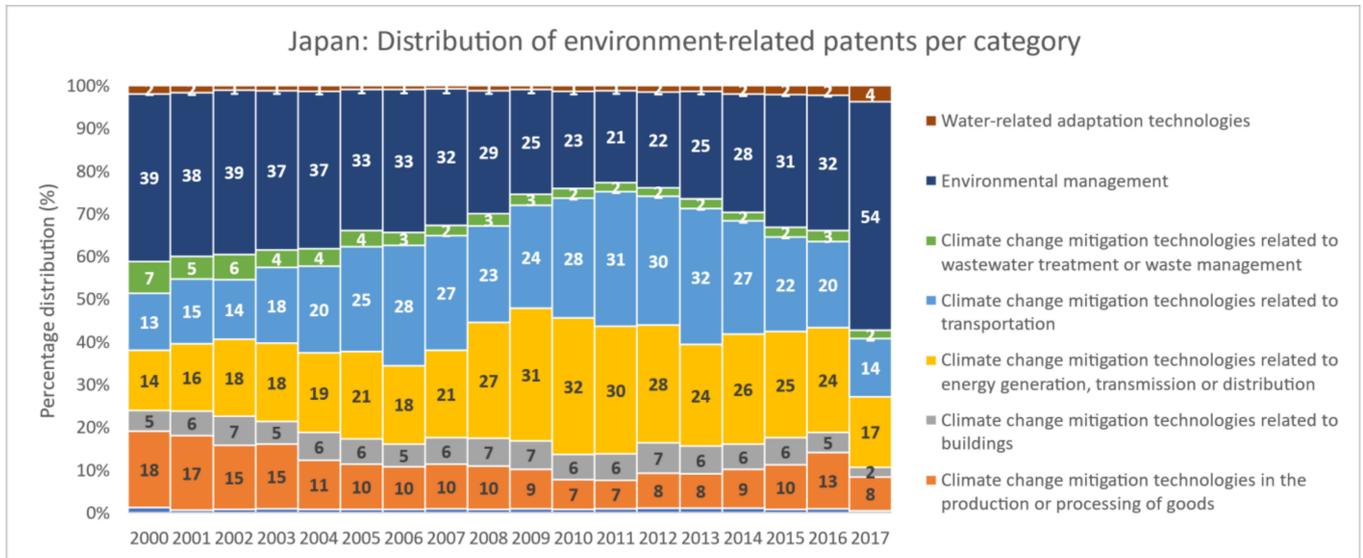


**Figure 4.** Percentage distribution of environment-related patents in China by category from 2000 to 2017. Source: own study based on OECD (2021), “Patents in environment-related technologies: Technology indicators”, OECD Environment Statistics (database), <https://doi.org/10.1787/e478bcd5-en> (accessed on 24 January 2021).

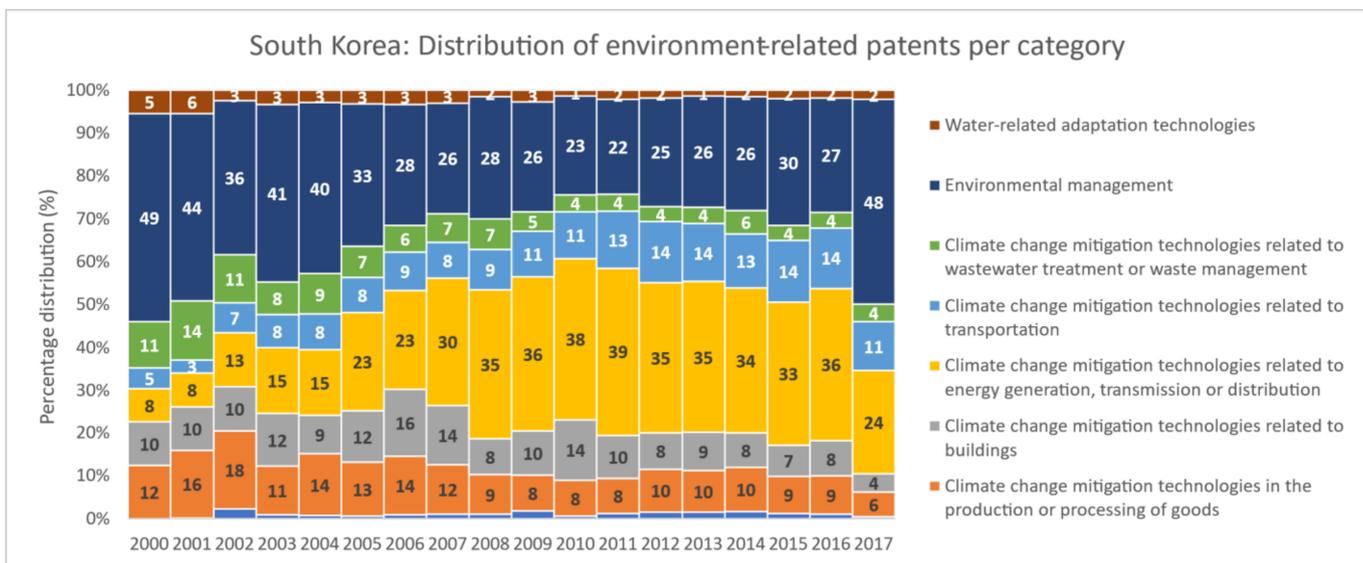


**Figure 5.** Percentage distribution of environment-related patents in Germany by category from 2000 to 2017. Source: own study based on OECD (2021), “Patents in environment-related technologies: Technology indicators”, OECD Environment Statistics (database), <https://doi.org/10.1787/e478bcd5-en> (accessed on 24 January 2021).

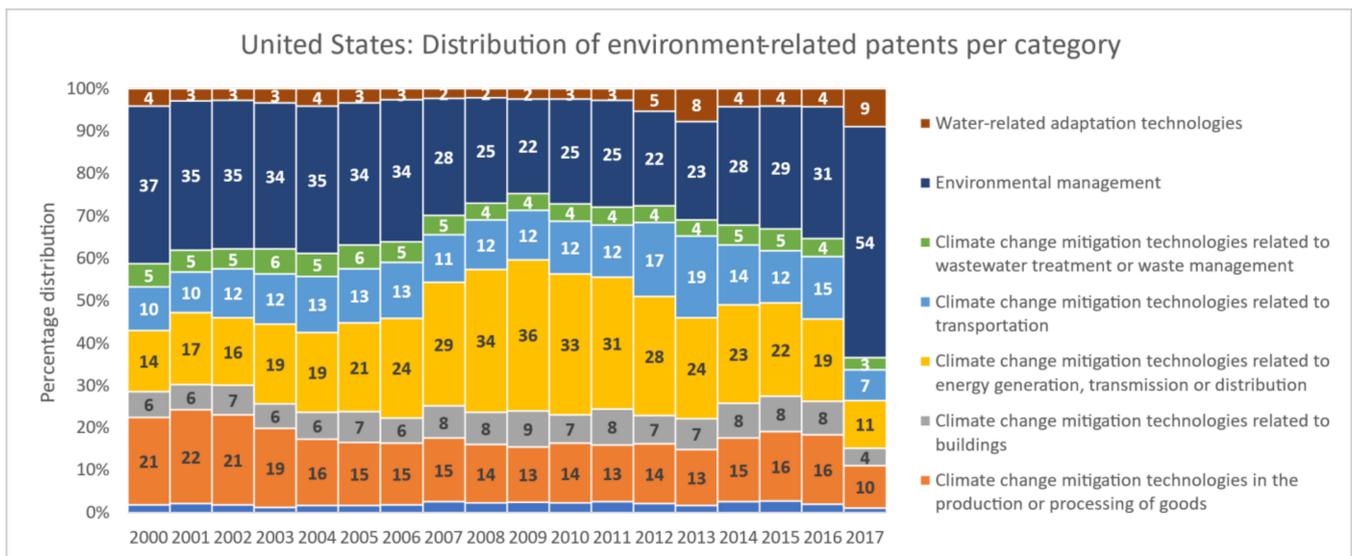
By contrast, the categories of climate change mitigation technologies related to wastewater treatment or waste management and water-related adaptation technologies had the smallest share in all the analysed economies (Figures 4–8).



**Figure 6.** Percentage distribution of environment-related patents in Japan by category from 2000 to 2017. Source: own study based on OECD (2021), “Patents in environment-related technologies: Technology indicators”, OECD Environment Statistics (database), <https://doi.org/10.1787/e478bcd5-en> (accessed on 24 January 2021).



**Figure 7.** Percentage distribution of environment-related patents in South Korea by category from 2000 to 2017. Source: own study based on OECD (2021), “Patents in environment-related technologies: Technology indicators”, OECD Environment Statistics (database), <https://doi.org/10.1787/e478bcd5-en> (accessed on 24 January 2021).



**Figure 8.** Percentage distribution of environment-related patents in the United States by category from 2000 to 2017. Source: own study based on OECD (2021), “Patents in environment-related technologies: Technology indicators”, OECD Environment Statistics (database), <https://doi.org/10.1787/e478bcd5-en> (accessed on 24 January 2021).

Considering the different countries with regard to the various technology domains, there were evident differences among these countries. In the case of China, environmental management technologies have been very important in recent years, but climate change mitigation technologies related to energy generation, transmission or distribution dominated between 2008 and 2011. In Germany, the systematic growth of environmental technologies was observed from 2000 to 2017, although climate change mitigation technologies related to transportation have played an important role since 2013; however, in the years 2009–2012, climate change mitigation technologies related to energy generation, transmission or distribution were dominant. Likewise, as in Germany, Japan has also shown a significant increase in the number of patents for environmental management since 2014, with mitigation technologies related to energy generation, transmission or distribution dominating from 2009 to 2010, whereas mitigation technologies related to transport dominated from 2011 to 2013. Figure 7 shows that although South Korea ranked fourth among the surveyed countries in the area of environmental technology in 2017, the important role of climate change mitigation technologies related to energy has been systematically evident since 2003. Similar to Germany and Japan, the United States also indicated a 54% share of environmental technologies in 2017. However, patenting of environmental technologies was dominant between 2007 and 2013. In the period 2000–2002, climate change mitigation technologies in the production or processing of goods ranked second.

## 5. Discussion

The key research question was twofold: (1) how does the development of eco-innovation based on environmental patents in green technologies evolve and (2) how can the output of technological eco-innovations be measured? In order to analyse the trends in environment-related technologies with regard to technology, economic and demographic development dynamics, the following indicators were constructed: (1) the share of environment-related patents in the total number of patent applications, (2) the number of environment-related patents per one million residents, (3) the number of environment-related patents per USD 100 billion, and (4) the distribution of environment-related patents per green technology category. The selection of these indicators resulted from the growing importance of the development of green technologies that are closely linked to environmental policies, e.g., in the field of climate change mitigation and the green transformation of industry.

This research design is distinguished from other studies published in recent years. There are various studies in the literature on eco-innovation that have focused on environmental-related patents [21,23,46,49,51–53], however, they often focus on only one country or a different research perspective.

The study contributes to the literature on measuring the output of eco-innovation in many ways. Firstly, the study covered a broad research perspective from 2000 to 2017 with the most up-to-date data, which sets this study apart from others. Similar studies mostly concerned a different timeframe perspective and research scope. For instance, Wang et al. (2019) focused on the period from 2000–2015 in China. They indicated that environmental-related technology innovation in China has made great advancements and has been at the forefront of green technology growth. Sterlacchini [54] examined trends and determinants of energy innovations based on the analysis of the relationship between energy patents, environmental policy and oil prices on a panel of 19 OECD countries between 1990–2013. Reffeira et al. [52] used country-level aggregate data collected by the OECD between 2000 and 2013 for 23 countries. They demonstrated that technological innovation can respond effectively to changes in key climate conditions. In doing so, they sought to contribute to the knowledge of innovation in the European context that stimulates economic growth while protecting the environment.

Secondly, this study referred to the world's leading patenting countries, i.e., the United States, Germany, China, Japan, and South Korea. Based on the analyses performed, in the case of patent applications per million inhabitants in the years 2000–2017, a downward trend can be seen after 2010. A similar downward trend over the analysed period can be observed in the share of environment-related patent applications in the total number patents as well as in case of patent applications worth USD 100 billion of GDP. These results are in line with other studies that also showed a declining trend in the share of environment-related patents after 2010 [55,56]. There are many reasons for this decline. One of the reasons for the decline may have been regulatory issues or the time lag between patent application and grant, as happened in South Korea [57]. Another discouraging factor could be the oversupply of some innovative energy equipment (e.g., solar panels, due to mass production in China), which has reduced the margins of companies operating in these markets [54]. The decline in environmental patents may be also due to a temporary reduction in incentives to invest in such areas as solar energy, as well as a partial exhaustion of technological opportunities. Another reason can be found in the increasing environmental awareness at political, business and public levels. This leads to the implementation of other, less costly practices related to the sustainable development paradigm. For instance, some countries such as Germany have reduced subsidies for renewables, while federal funding for clean energy has been cut significantly in the US (31% reduction in funding for the Environmental Protection Agency) [54]. This decline in the number of patent applications after 2011 was most likely the result of the financial crisis [49].

Thirdly, for the purposes of data analysis, the study provides a comprehensive overview of changes and trends in the development of environmental technologies. In order to assess the extent to which these countries indicate a shift towards sustainability through technological eco-innovation, it was necessary to analyse the different technology domains. All of the analysed countries had the highest number of patents in the field of environmental management, with Germany, Japan and the United States at the forefront. The second-largest number of patents was in the field of climate change mitigation technologies related to energy generation, transmission or distribution. South Korea and Japan are the leaders in this sphere. The third technology domain was climate mitigation technologies related to transportation, where Germany has recently taken the leading position while the United States ranked last. Another domain is climate change mitigation technologies in the manufacture or processing of goods. In this area, the highest number of patents was registered in China and the United States, and the lowest in South Korea. With regard to climate change mitigation technologies related to buildings, China has the leading position and Germany the last. The remaining technologies with the smallest share

of environmental technology patents are water-related treatment or waste management, as well as water-related adaptation technologies. Patents on climate change mitigation technologies related to wastewater treatment or waste management were registered most frequently in South Korea, while the highest number of water-related adaptation technologies occurred in the United States. This is all the more remarkable as developed countries and an increasing number of developing countries face the challenge of ensuring access to water, especially in terms of physical access. In the case of the analysed economies, this challenge predominantly concerns China [46].

This study has also demonstrated that patent data can be useful for measuring the effectiveness of innovation policies. It shows not only how many patents are actually registered, but also which environmental technologies are diffused and legally protected internationally. The environmental technologies analysed cover a broad spectrum of technologies related to environmental pollution, water scarcity and climate change mitigation. These technologies are closely linked to environmental policies such as climate change mitigation and the green transformation of industry. For example, different national governments have already developed programs to facilitate the development and diffusion of climate change mitigation technologies [58,59].

Furthermore, environmentally friendly technologies have been developed in response to clear, strong government support in the form of tax incentives, R&D subsidies, favourable regulatory frameworks and government spending policies [52]. Therefore, technological development requires investment from both the public and private sectors. Given the output of technological eco-innovation, this research also contributes to the debate on technological competition as well as on the development of eco-innovation policy research.

## 6. Conclusions

Growing ecological awareness of society and pressure from stakeholders require entities to implement eco-innovation, including technological eco-innovation [60]. The aim of this paper was to measure the output of technological eco-innovation and to analyse the trends in green technologies based on environment-related patents in the world's leading countries from 2000 to 2017. Based on patent data from the OECD, the comparative analysis of the world's leading countries in patenting (i.e., United States, Germany, China, Japan, and South Korea) was conducted. In line with this, the differences in the development of environmental technologies in the best-patenting countries in the world were first analysed, and an assessment was subsequently made of the extent to which these countries indicate a shift towards sustainable development through technological eco-innovation.

This analysis provides a comprehensive overview of the changes in the development of environmental technologies in the selected countries. Regarding the share of environment-related patents in the overall number of patent applications, the development trends were varied. In particular, the years 2009–2011 presented the highest level, whereas there was a drastic decline between 2016 and 2017. The highest rate was observed in Germany and the lowest in the United States. Given the application per million residents, development was also varied. The highest trend can be observed in Japan between the years 2009 and 2016, with a significant decrease not only in Japan but also in South Korea and Germany since 2016. The lowest rate was observed in China. For the ratio of patent applications per 100 billion GDP, the highest ratio was observed between the years 2009–2016 in Japan, although a drastic decrease was observed from 2016–2017 in Japan, South Korea and Germany. The lowest rate between the years 2000–2017 was observed in China.

Furthermore, this study shows different results in the investigated countries regarding the number of patents of environmental technologies. For instance, environmental management as well as climate change mitigation technologies related to energy generation, transmission or distribution have dominated in the selected countries recently. In contrast, the categories of climate change mitigation technologies related to wastewater treatment or waste management and water-related adaptation technologies had the smallest share in all analysed economies. The progress in patenting eco-innovations using the example

of environmental technologies varied across these world's leading economies, but a significant share of their eco-innovation development was evident in order to meet current environmental challenges through the effective implementation of innovative technologies. These indicators also enable the assessment of innovation performance in policy research. Therefore, this study provides valuable information to stakeholders interested in environmental technologies and gives policy makers perspectives on different technology options. However, the findings on the development of environmental technologies in the leading countries in patenting suggest that a complete reliance on green technologies is still at an early stage despite some progress observed over the last two decades.

In conclusion, the transformation process toward sustainable development can be achieved by eco-innovation that results in the reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives [61]. Eco-innovation refers to a broad set of innovations, e.g., renewable energy technologies, pollution prevention systems, waste management equipment, green financial products and biological agriculture [62]. In particular, technological eco-innovation plays an important role in sustainable society, promoting economic development and pollution control.

As with any other study, it should be noted that there are limitations that need to be addressed in future research. In particular, our study is based solely on secondary data and focuses only on five selected countries. Therefore, future research can apply our framework in other contexts, considering different variables and dimensions. Additional research on the impact of technological eco-innovation on sustainability also seems to be an important point to raise. It would help, for example, to clarify what factors influence patent use or what political factors may influence environmental patents. Any contribution in this area would be an important addition to this study.

Despite the fact that there is already some evidence of a knowledge base for eco-innovation focused on environmental patents [21,23,46,49,51–53], there is still no comprehensive review of the knowledge base of patents regarding different environmental technologies. Patent indicators can provide knowledge about which countries are investing in specific technologies and identify potential eco-innovation trends. Therefore, a broader context beyond patent analysis is recommended and can be considered to make robust statements about specific trends in eco-innovative technologies. The indicators and methodology presented in this study can be used further for exploratory assessments in specific technological domains.

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