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# Convergence of Environmental Technologies: The Case of OECD

## *Çevre Teknolojileri Yakınsaması: OECD Örneği*

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## ÖZ

Bu çalışmanın amacı, çevre teknolojileri yakınsamasını stokastik yakınsama ile incelemektir. Analiz, 1992-2022 yılları arasındaki veriler kullanılarak Kesirli Fourier Birim Kök Testi ile gerçekleştirilmiştir. Analize 31 OECD ülkesi dahil edilmiştir. Bulgular, çevre teknolojileriyle ilgili patentlerin 23 ülkede OECD ortalamasına yakınsadığını göstermektedir. 8 ülkede yakınsama görülmemektedir. Ülkelerin yaklaşık %75'inde yakınsama olduğu göz önüne alındığında, ortak bir politika izlenmesinin olumlu sonuçlar verebileceği söylenebilir. Ancak yakınsamanın olmadığı 8 ülke göz önüne alındığında, bu ülkelerin ortak stratejilerin yanı sıra ek, ülkeye özgü politikalar geliştirmeleri yararlı olacaktır.

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## ABSTRACT

The aim of this study is to examine environmental technology convergence with stochastic convergence. Analysis was conducted using Fractional Fourier Unit Root Test using data from 1992 to 2022. 31 OECD countries were included in the analysis. The findings indicate that patents related to environmental technologies converge to the OECD average in 23 countries. Convergence is not observed in 8 countries. Given that convergence exists in approximately 75% of countries, it can be said that pursuing a common policy could yield positive results. However, considering the 8 countries where convergence is not present, it would be beneficial for these countries to develop additional, country-specific policies alongside common strategies.

## 1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC), which was opened for signature at the Earth Summit held in Rio in 1992, entered into force in 1994 (United Nations, 1992; United Nations Climate Change). The UNFCCC became operational with the adoption of the Kyoto Protocol in 1997, which entered into force in 2005. The Protocol was implemented in two commitment periods. During the first period, from 2008 to 2012, 37 industrialized countries, economies in transition, and the European Union—listed in Annex B of the agreement—committed to reducing their overall greenhouse gas emissions by at least 5% compared to 1990 levels. Additionally, each country was assigned specific, quantified emission reduction or

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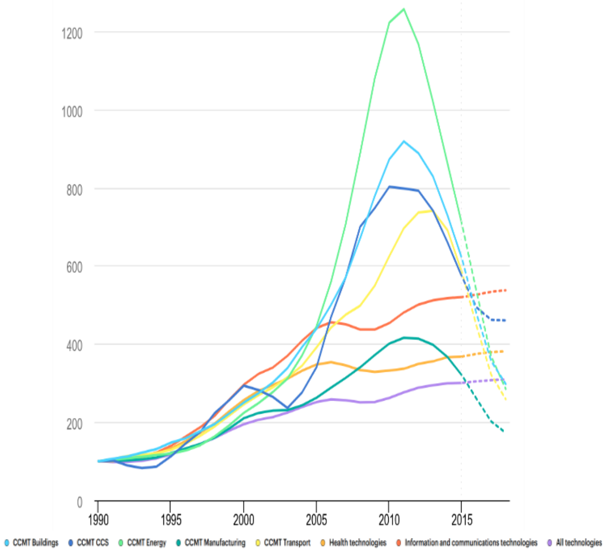
limitation targets. The Protocol is based on the principle of "common but differentiated responsibilities and respective capabilities" as outlined in the UNFCCC (UNFCCC, 1997). In the second period covering 2013-2020 held in Doha in 2012, it was agreed that emissions would be reduced by at least 18% in 2020 compared to 1990 levels. Australia, Canada, Japan, and Russia, which had obligations in the first period, did not assume any obligations in the second period (Akanle et al., 2012). The second commitment period came into effect on December 31, 2020, with the signatures of the signatory states (United Nations Treaty Collection, 2025). The Paris Climate Agreement, which was adopted by 195 countries in 2015 and entered into force in 2016, is based on the United Nations Framework Convention on Climate Change following the Kyoto Protocol and aims to strengthen global socio-economic resilience in the fight against climate change. It is a legally binding agreement on climate change. Due to its legally binding nature for all countries that are party to the agreement, it is a turning point in the global fight against climate change. Under the agreement, countries have been submitting their 5-year climate actions based on their Nationally Determined Contributions since 2020. In their National Determined Contributions, countries present their actions to reduce greenhouse gas emissions in order to achieve the Paris Agreement targets, as well as the strategies they will develop to ensure resilience to climate change. The Paris Agreement provides a framework for supporting countries that need financial, technical, and capacity-building support. The long-term objective of the Paris Agreement is to limit the rise in global temperatures to well below 2°C above pre-industrial levels, with efforts to restrict it to 1.5°C (UNFCCC, 2015).

To limit global warming to around 1.5°C, global greenhouse gas emissions must reach their peak before 2025 at the latest, reduce by 43% by 2030, and reduce methane emissions by approximately one-third. Global temperatures will stabilize if carbon dioxide emissions reach net zero. This means that if global temperatures are limited to 1.5°C, global net-zero carbon dioxide emissions will be achieved by the early 2050s (IPCC, 2022). While solutions have been found to halve emissions by 2030, achieving net-zero emissions by 2050 requires significant and rapid technological innovation (WIPO, 2023). Significant innovative efforts are needed to bring these new technologies to market in a timely manner.

By country Japan, Germany, China, Republic of Korea and United States represent approximately 76% of high-value climate mitigation innovation. In particular, patent applications in China are increasing. Approximately 90% of climate innovation is generated by 10 countries. The nine countries other than China are high-income countries (WIPO, 2023). The United States, Europe, Japan, Korea, and China account for over 90% of global renewable energy patents. Transferring this technological knowledge from developed countries to developing countries will contribute to achieving net-zero emissions targets (IEA, 2021). Patent applications related to technologies aimed at mitigating climate change are presented in Figure 1.

**Figure 1.** Worldwide patent trends in climate change mitigation technologies, 1990–2015

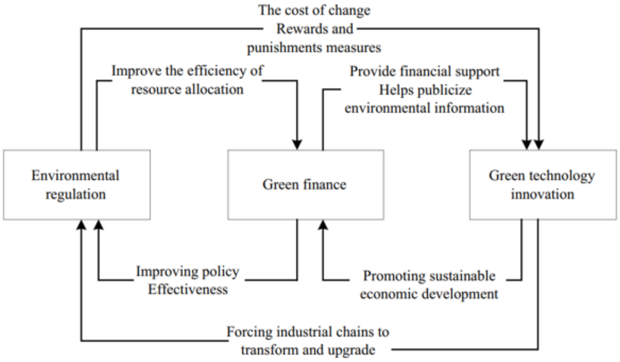


**Source:** IEA (2019).

When examining Figure 1, it can be seen that patents in the energy sector are the most frequently applied for area in terms of reducing climate change. The acquisition of green technology has an impact on non-residential $CO_2$ emissions. These technologies increase companies' green R&D capabilities and contribute to long-term emission reductions. When intellectual property protection exceeds a certain threshold, the carbon-reducing effect of green technology adoption becomes more pronounced (Fei et al., 2024). The carbon capture, utilization and storage (CCS) sector is also a prominent area in patent applications.

Technological innovation is seen as the most important way to mitigate climate change and reduce carbon emissions. Furthermore, technological innovation is an endogenous driving force in green economic development (Fawzy et al., 2020). Green technology innovation faces greater risks compared to traditional technology innovation. It has more uncertain short-term returns. It also requires higher capital investment in R&D. Even if businesses have the desire and potential for innovation, the lack of financial support makes it difficult to carry out green innovation activities (Lu et al., 2022; Zeng et al., 2023). In this regard, green finance plays a decisive role in the development and implementation of environmental technologies. Green finance, a sustainable financial system that considers the long-term effects of investments on people and the environment, aims to provide the financial infrastructure to facilitate the transition to a low-carbon, climate-resilient economy. Therefore, green finance supports socially beneficial and ecologically sustainable initiatives. This financing contributes significantly to reducing carbon emissions (Umar and Safi, 2023). The green finance market includes financial products aimed at controlling harmful emissions (Wang and Zhi, 2016). Green finance supports high-quality economic development and the development of green technology by strengthening the ecological environment, economic activity, and economic structure (Yang et al., 2021). Green technological development promotes sustainable economic development. Therefore, green finance and green technologies interact with each other. Environmental regulations affect green finance by improving the efficiency of resource allocation, which in turn increases policy effectiveness. Environmental regulations transform operating costs through reward and infliction systems. They also support the green transformation and renewal of the regional industrial chain. Thus, they provide a foundation and driving force for the sustainable development of the regional economy (Liu and Nie, 2022). The impact mechanism between green finance, green innovation, and environmental regulation is shown in Figure 2.

**Figure 2.** Green Finance, Green Innovation and Environmental Regulation Mechanism



**Source:** Liu and Nie (2022)

Green financing support has a positive impact on the increase in green technology patents and utility models (Lu et al., 2022; Zhang et al., 2025). The Paris Climate Agreement has paved the way for the commercialization of clean technology patents globally. Clean technologies in various fields such as renewable energy, smart grid technologies, green chemistry, and water purification are protected by more than 500,000 patents globally (Linnenluecke et al., 2016). Green financing is needed to commercialize these patents and achieve environmental improvement. The need for green technological transformation to strengthen environmental regulations, promote green economic transformation, and ensure sustainable growth also creates a need for financing (Lv et al., 2021). Global climate finance has nearly doubled in the last decade (2011-2020) to $4.8 trillion. It is estimated that in 2021, it will be in the range of $850-940 billion, with an equal distribution between the public and private sectors. While climate finance has a cumulative average annual growth rate of 7% (CAGR), this rate falls far short of meeting the target of keeping global temperatures below 1.5°C to prevent global climate change. To avoid the worst global impacts of climate change, it is estimated that annual financial flows must reach at least $4.3 trillion by 2030. This indicates the necessity of a 21% annual growth rate in global climate finance (Naran et al., 2022).

## 2. Theoretical Framework

Some economic models have begun to be reshaped by incorporating various environmental factors due to environmental issues. Kuznets' (1955) study examining the relationship between income distribution and growth has been reshaped by Grossman and Krueger (1991) and Panayotou (1993) based on environmental factors. This approach is based on the hypothesis that there is an inverse U-shaped relationship between income level and environmental pollution; environmental pollution will begin to decrease after a certain income level. Environmental constraints have also begun to be included in growth models (Acemoglu et al., 2012; Brock and Taylor, 2010). Convergence hypotheses are another prominent topic in the economic treatment of environmental pollution. Convergence theories are based on the Solow (1956) model. According to the Solow model, income differences between high- and low-income countries will converge over time due to economies of scale. Based on convergence theory, environmental convergence has also begun to be analysed in a manner similar to the economic convergence model. In other words, the assumption that the environmental quality of countries will converge over time is examined as "environmental convergence." The Green Solow model proposed by Brock and Taylor (2010) suggests that conditional convergence of pollutant emissions will occur, using an approach similar to conditional income convergence. According to the environmental convergence hypothesis, although developing countries initially experience greater environmental degradation, in the long term, they converge towards the environmental quality of developed countries. In other words, environmental convergence occurs because countries with low per capita emissions tend to increase their emission levels, while countries with high per capita emissions tend to reduce their emission levels (Brock and Taylor, 2010). Environmental convergence studies are examined based on econometric models. It can be said that the first study examining convergence using environmental pollution indicators was conducted by Strazicich and List (2003), which empirically examined the convergence of carbon dioxide emissions using the stochastic convergence approach (Solarin et al., 2021). In the last two decades, carbon emissions (Lee et al., 2023; Barassi et al., 2011; Lee and Chang, 2008; Aldy, 2006), ecological footprint (Shahbaz et al., 2025; Bayraktar et al., 2023; Yilanci and Pata, 2020; Solarin, 2019; Yilanci et al., 2019), renewable energy (Pinar, 2024; Zhang et al., 2021; Kasman and Kasman, 2020; Solarin et al., 2018), environmental technologies (Henriques et al., 2025; Solarin et al., 2025; Costantini et al., 2023). Stochastic convergence studies provide information about the policies to be followed at the micro or macro level and the effectiveness of these policies. They enable decisions to be made about whether the policies to be applied regarding the indicator in question should be common or individual. The existence of convergence also provides information about the policies to be followed globally.

## 3. Literature

Convergence analyses attempt to demonstrate the existence of convergence using different indicators. There are studies that examine the convergence of environmental technologies using different indicators such as the ecological innovation index and patent applications related to renewable energy.

When examining studies that address ecological innovation in technological convergence using different indicators, Henriques et al. (2025) evaluated the eco-innovation performance of European Union (EU) member countries. They also revealed the convergence trends of countries in this area. Data envelopment analysis was used in the study, which examined the period from 2016 to 2023. Eco-innovation efficiency was measured dynamically over time, and these measurements were combined with club convergence to form clubs. The analysis identified two clubs. The first club consists of countries with high levels of efficiency. It also shows more unstable but generally higher eco-innovation performance over time. The second club includes countries with lower levels of efficiency and generally structural problems (e.g., funding inefficiency, inability to reduce environmental impacts). The findings indicate that EU eco-innovation policies do not have similar effects across all countries and therefore, policy instruments should be differentiated across clubs. Torrecillas et al. (2024) examined ecological innovation convergence, covering both input and output variables, using the club approach. In the study, which focused on EU countries, the ecological innovation index was used as an indicator. The findings show a positive relationship between ecological innovation and R&D personnel, as well as between environmental protection expenditures and material efficiency, while indicating a negative relationship between environmental protection expenditures and green innovation. Bai and Lin (2024) examined the green innovation performance of China's 30 provinces using club convergence and social network models. The convergence analysis results revealed a divergence trend in green innovation efficiency across the entire sample. This indicates that differences between regions are not closing naturally. Three clubs were identified for the 30 provinces: high efficiency, medium efficiency, and low efficiency. The results of the analysis within each club show that each club has statistically significant β-convergence. Considering this result, it indicates that club members will approach similar efficiency levels over time, but differences between clubs will remain permanent. The study reveals that uniform convergence does not apply to green innovation efficiency and that regional differences are becoming permanent within a club-based structure. This situation highlights the necessity of implementing club-focused, differentiated strategies for the dissemination of green innovation in terms of policy design. This is because low-efficiency clubs cannot close the gap with high-efficiency clubs, even if they show development within themselves. Costantini et al. (2023) examined ecological innovation convergence for EU countries using the club convergence approach. The study, which covers the period 2012-2021, used the ecological innovation index as an indicator. Three convergence clubs were identified for the index. The number of clubs varied between 4 and 5 across the five sub-dimensions of the index. The results indicate that eco-innovation performance does not develop homogeneously across countries; on the contrary, certain clusters (clubs) emerge. Therefore, it is emphasized that uniform policy applications may be insufficient, and country-specific strategies may be more effective. Chatzistamoulou and Koundouri (2022) examined resource productivity and eco-innovation performance in their study to achieve sustainable and inclusive growth targets for the EU-28 countries within the framework of the European Green Deal. The period 2000-2019 was considered. Club convergence was used. The results obtained show that there are significant differences between countries in terms of eco-innovation performance. In this context, five different clubs were identified. This heterogeneity and the clubs must be taken into account when determining policies. Karman et al. (2020) examined the absolute β-convergence of eco-innovation between developed and developing countries. 38 countries were analysed, covering the period from 2012 to 2017. The analyses result show convergence in the overall level of eco-innovation. This means that countries with relatively low eco-innovation indices can create or imitate new eco-innovations more quickly than eco-innovation pioneer countries. In other words, these countries benefit from a "laggard advantage." The results also indicate that eco-innovation has positive spillover effects.

When examining studies that demonstrate convergence based on patent data in environmental technological convergence analyses, Solarin et al. (2025) examined environmental innovation convergence for 21 EU countries and the United Kingdom. The study, which covered the period 1992-2021, used three different convergence tests (beta, stochastic, and sigma). The stochastic convergence test examined whether countries adopted common policies in the long run. Beta convergence examined whether countries with lower environmental innovation at the outset converged towards better-performing countries, while sigma convergence examined whether consolidation increased as a result. Environmental innovation intensity and environmental innovation per capita indicators were used. Environmental technology patents per million people were used as an environmental innovation indicator. The total patents filed for environment-related technologies per billion real GDP (using 2015 US$ prices) was used as an environmental innovation intensity indicator. The results obtained from the three convergence approaches generally indicate environmental innovation convergence. The beta convergence results reveal that CO2 emissions, institutional quality, GDP per capita, and financial development specific to each country are effective on environmental innovation. When the United Kingdom is excluded from the analysis, convergence is observed in 17 out of 21 countries using patents per million people for environmental technologies as an indicator. When the United Kingdom is included in the analysis, convergence is observed in 16 out of 22 countries excluding the United Kingdom. In the trend model, convergence is observed in 15 out of 21 countries. The convergence analysis results for the indicator "total patents filed for environment-related technologies per billion real GDP (using 2015 US$ prices)" show convergence in 17 out of 21 countries in the fixed model and in 17 out of 22 countries when the United Kingdom is included in the analysis. In the trend model, convergence is observed in 14 out of 21 countries. When the United Kingdom is included, convergence is observed in 15 out of 22 countries. Pinar (2024) used the club convergence approach to examine renewable energy convergence for 90 countries. Patents for renewable energy filed with the triadic patent family (Europe, Japan, and the US) were used as indicators. The results obtained show that there is no convergence in renewable energy innovation at the panel level. Therefore, it can be said that there is no global convergence. Furthermore, the findings suggest that there is a club of more innovative countries and a second club of less innovative countries. Additionally, the findings show that there is a club of more innovative countries and another club of less innovative countries. It has been found that countries with higher per capita income, research and development (R&D) investment, better environmental regulations, and stronger institutional structures are more likely to be part of the innovative club. Countries that increase R&D investments and environmental regulations and improve their institutional quality can increase their likelihood of joining the innovative club. In addition, these less innovative countries can develop policies to transfer renewable energy technologies from innovative countries. Kijek et al. (2021) examined whether convergence existed in energy innovation in 27 European countries between 2000 and 2018. Patent applications for energy technologies aimed at combating climate change were used as an indicator in the convergence analysis. The club convergence approach was adopted to determine technological convergence between countries. The findings indicate that there is no general (absolute) convergence between countries. Three different clubs were identified. Factors such as per capita environmental R&D expenditures, human resources in science and technology, and the stringency of environmental policies were identified as determinants of this clustering. It was emphasized that innovation inequality between countries persists and that some countries benefit from the innovation efforts of others. It is recommended that country-specific and smart specialization strategy-based policies be developed to support low-performing countries. Bai et al. (2020) analysed whether there was convergence in the levels of technological innovation in 30 provinces in China using data from 1997-2015. Sigma convergence was used to examine whether innovation differences between provinces decreased over time. To test whether provinces with low innovation levels were catching up with other provinces by growing faster, beta convergence analysis was used. Sigma convergence was not achieved, meaning that there was no absolute trend toward equalization among provinces. However, beta convergence was observed. This indicates that provinces with low innovation levels have the potential to catch up with high-performing provinces. Additionally, when considering the spatial beta convergence results, it was found that the innovation levels of neighboring regions influence each other, creating a spatial spillover effect. The results emphasize the need for innovation policies to be implemented in a supportive manner not only in central provinces but also in peripheral and low-performing regions. Grafström (2018) examined per capita renewable energy convergence for EU countries. The period from 1990 to 2012 was analysed using patent data from 13 EU countries. Conditional beta and sigma results for the 13 EU countries indicate a lack of convergence. However, there is divergence. There is heterogeneity across member states regarding renewable energy patents. Therefore, it is noted that this may raise concerns about the sustainability of the policies implemented as a whole. Yan et al. (2017) examined low-carbon technology convergence in their study. They analysed 72 countries for the period 1990-2012 and 19 OECD countries for the period 1960-2012. Patent applications in this field were used as an indicator of low-carbon technology. The convergence analysis results did not provide evidence of convergence for the 72 countries. Looking at the results for club convergence, there are 6 convergent clubs in terms of low-carbon technology stocks. In terms of the intensity of low-carbon technology stocks, 3 convergent clubs were identified. For the 19 OECD countries, the convergence hypothesis could not be rejected. Zhang et al. (2021) examined the renewable energy efficiency and convergence of 20 Latin American countries. Beta and sigma convergence were used. In two subregions, there is no convergence or absolute beta convergence in the growth of total factor productivity in renewable energy, but there is significant conditional convergence.

## 4. Data Set and Method

This study examines the convergence of environmental technologies with stochastic convergence. In this context, the ratio of environmental inventions to all domestic inventions in all technologies was used as an indicator. 31 OECD countries were included in the analysis. The number of countries was determined based on whether they had data for the period under consideration. In some years, countries with missing data were excluded from the analysis. The starting year was determined based on the earliest data set available and the need to include the largest country. The period from 1992 to 2022 was considered. The data in question was obtained from the OECD.

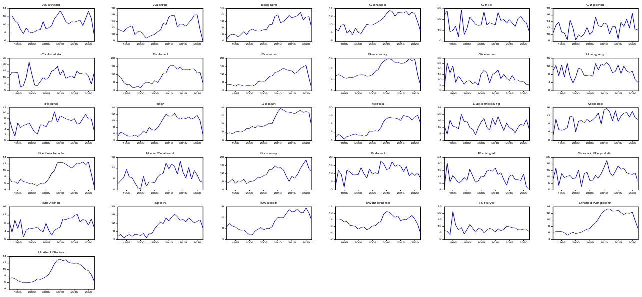
Patent indicators are used in econometric analyses to compare technological advancement between regions and to analyse innovation performance worldwide. This indicator is an internationally standardized indicator. While broad-based patent indicators are used, patent counts specific to particular fields are also used in the literature (Haščič et al., 2015). Patent statistics and indicators enable the tracking of innovations in environmental technologies. These statistics not only facilitate the evaluation of countries' environmental and innovation policies but also provide insight into the approaches taken by governments (OECD, 2025).

**Table 1:** Descriptive Statistics

| Country | Min. | Max | Mean | Median | Std. Dev. | Kurtosis | Skewness |
|---|---|---|---|---|---|---|---|
| Australia | 7,5585 | 13,4782 | 10,3709 | 10,6992 | 1,6331 | -0,8845 | 0,0505 |
| Austria | 8,0976 | 16,1226 | 12,2134 | 11,9499 | 2,2068 | -0,6354 | 0,2866 |
| Belgium | 4,7348 | 12,9017 | 8,7638 | 7,8415 | 2,4498 | -1,4276 | 0,0968 |
| Canada | 7,6319 | 13,5367 | 10,7055 | 10,3170 | 1,9456 | -1,4488 | 0,0153 |
| Chile | 3,9840 | 29,0322 | 17,1861 | 16,8454 | 6,2488 | -0,2442 | -0,0167 |
| Colombia | 2,6845 | 21,8750 | 11,4011 | 11,3651 | 4,4502 | 0,14552 | -0,1208 |
| Czechia | 8,2788 | 16,5286 | 11,9034 | 12,1010 | 2,0450 | -0,3030 | 0,1454 |
| Finland | 5,3711 | 16,6097 | 10,8273 | 10,5533 | 3,6946 | -1,5341 | 0,0552 |
| France | 4,8415 | 16,4702 | 10,1963 | 9,4393 | 3,5893 | -1,5102 | 0,2236 |
| Germany | 6,0772 | 15,7983 | 11,7458 | 9,9435 | 2,8977 | -1,4687 | 0,1051 |
| Greece | 3,6363 | 25,4891 | 11,6314 | 9,8111 | 5,4128 | 0,12835 | 0,7492 |
| Hungary | 3,7950 | 13,9314 | 9,5714 | 9,5630 | 2,8484 | -0,8447 | -0,2204 |
| Ireland | 1,5585 | 10,6106 | 6,4022 | 6,4854 | 2,1019 | -0,0064 | -0,3691 |
| Italy | 5,1333 | 12,3409 | 8,5401 | 7,9684 | 2,5505 | -1,7433 | 0,0066 |
| Japan | 7,6180 | 13,8497 | 10,5968 | 9,8111 | 2,1707 | -1,6835 | 0,1403 |
| Korea | 4,4743 | 16,3286 | 10,5396 | 8,7555 | 4,1635 | -1,7802 | 0,1117 |
| Luxembourg | 7,4362 | 19,9244 | 13,1539 | 12,6436 | 3,0975 | -0,3515 | 0,2410 |
| Mexico | 2,6143 | 15,7756 | 10,2414 | 10,3236 | 3,3851 | -0,3384 | -0,4729 |
| Netherlands | 5,1745 | 12,6446 | 8,7886 | 7,5829 | 2,8060 | -1,7596 | 0,1918 |
| New Zealand | 4,1935 | 14,6384 | 9,0437 | 8,7765 | 2,6919 | -0,5298 | 0,3187 |
| Norway | 7,0727 | 18,7646 | 11,2732 | 10,6680 | 3,2055 | -0,7276 | 0,5225 |
| Poland | 1,7569 | 17,6244 | 11,1137 | 10,6602 | 3,6153 | 0,86150 | -0,4720 |
| Portugal | 4,5030 | 20,5673 | 11,6239 | 11,6436 | 3,6769 | 0,00489 | 0,2203 |
| Slovak Republic | 2,5751 | 22,5906 | 11,8600 | 12,3932 | 4,3245 | 0,48019 | 0,0579 |
| Slovenia | 1,1029 | 12,5647 | 7,1133 | 6,1363 | 2,9363 | -0,8975 | -0,0552 |
| Spain | 4,7041 | 16,5036 | 10,1582 | 11,1559 | 3,8231 | -1,6492 | -0,0247 |
| Sweden | 5,7269 | 15,6590 | 10,3435 | 8,9621 | 3,1182 | -1,3735 | 0,2792 |
| Switzerland | 3,9076 | 10,5862 | 7,48245 | 7,5452 | 1,6833 | -0,6503 | -0,0525 |
| Türkiye | 3,8461 | 21,3953 | 8,1391 | 7,9269 | 3,0313 | 12,0527 | 2,6609 |
| United Kingdom | 5,3333 | 13,3654 | 9,1490 | 8,4628 | 2,9554 | -1,7820 | 0,1812 |
| United States | 5,9657 | 13,2273 | 9,1071 | 8,4306 | 2,6019 | -1,5871 | 0,2756 |
| Average of OECD | 7,2203 | 13,8341 | 10,1728 | 9,3017 | 2,5077 | -1,8293 | 0,1797 |

The descriptive statistics for the countries covered in the study are presented in Table 1. The share of environmental inventions among total inventions in OECD countries averages around 10%. Looking at the averages of the share of environmental inventions among total inventions in countries, this ratio is higher than the OECD average in 19 countries. The country with the lowest average is Ireland, while the country with the highest average is Chile. Ireland is followed by Slovenia and Switzerland. Switzerland has generally remained below the OECD average for the covered period. The OECD average peaked in 2013. Although there were fluctuations in the average between 2013 and 20201, there was no significant decline. Among OECD countries, Korea has seen the highest increase. The rate, which was 8.47 in 2008, rose to 10.23 in 2008 and to 16.33 in 2021. The trend over time for the countries during the period under review is shown in Figure 3.

**Figure 3.** The dynamics of the share of environmental inventions in total inventions for OECD countries (1992-2022)



### 4.1. Method

Stochastic convergence indicates whether a shock occurring over time for the relevant variable is permanent. Therefore, the stochastic convergence hypothesis is tested using unit root tests. If the series is found to be stationary, this supports convergence (Misra et al., 2024). The stochastic convergence test statistically examines whether there is convergence toward a common long-term equilibrium among the groups considered (Solarin et al., 2025). The stochastic convergence model is defined as follows (Meng et al., 2013; Baygın, 2017; Solarin et al., 2018; Pan and Maslyuk-Escobedo, 2018; Luo et al., 2023).

$$y_t = ln\left(\frac{EP_t}{AEP_t}\right) = (lnEP_t - lnAEP_t)$$

in this here EP shows the patent variable related to the environment. AEP shows the OECD patent average related to the environment, and t shows the year.

In this study, patents related to the environment were used as an environmental technology indicator. The convergence of this indicator was examined using the Fractional Fourier unit root test. Fractional frequency values indicate permanent breaks in the series. Integer frequencies indicate temporary breaks (Christopoulos and Leon-Ledesma, 2011). A fractional frequency unit root test was used in this study by Bozoklu et al. (2020). Since the test includes fourier functions in the model, it is not necessary to know the number, structure and location of structural changes. On the other hand, the test allows for fractional frequency values. Fractional frequencies cause permanent breaks in the series. Therefore, when the frequency value is a fractional process, traditional unit root tests may yield incorrect results. For this reason, the inclusion of fractional frequencies enables a more accurate assessment of the stationarity in the series. The test developed by Bozoklu et al. (2020) is an improved version of the Omay (2015) test. In the Omay (2015) test, the frequency is allowed to take fractional values between 0 and 2. In the unit root test developed by Bozoklu et al. (2020), the frequency values are still fractional, but the range is expanded to allow values between 0 and 5. The following model was estimated to apply the Fourier ADF unit root test (Bozoklu et al., 2020).

$$\Delta y_t = \beta_1 + \beta_2 sin(2\pi kt/T) + \beta_3 cos(2\pi kt/T) + \beta_4 y_{t-1} + \sum_{i=1}^{p} a_i \, \Delta y_{t-i} + u_t$$

t; trend, T is number of observation. To find the optimal value of k, values that increase by 0.1, 0.2, …, 5 are substituted for k, and it is decided that the k that gives the smallest KKT is the appropriate frequency value. Sin and cos represent trigonometric terms. Firstly, the significance of trigonometric terms representing the Fourier function is tested. The obtained test statistic is compared with the table values of Enders and Lee (2012). If the obtained test statistic is greater than the table critical value, it is concluded that the trigonometric terms are significant. If the trigonometric terms are significant, the series' stationarity is determined by comparing the table critical values of the test developed by Bozoklu et al. (2020) with the FADF critical value. If the trigonometric terms are not significant, the series' stationarity is determined by examining the classical ADF unit root test (Bozoklu et al., 2020).

## 5. Findings

The results of the fractional Fourier and ADF unit root tests are presented in Table 2 and Table 3. Table 2 shows the model with only the constant term, while Table 3 shows the unit root results for the model with both the constant and trend terms. FADF represents the test statistic for the fractional Fourier unit root test, while the ADF test statistic indicates the result of the ADF unit root test.

**Table 2:** Unit Root Test Results (Constant)

| Country | Freq. | Min KKT | F Test | Optimum lag | FADF Test Stat. | ADF Test Stat. |
|---|---|---|---|---|---|---|
| Australia | 0.6 | 0.183 | 11.321*** | 7.00 | -3.973** | -2.310 (0) |
| Austria | 0.5 | 0.204 | 7.6385** | 2.00 | -4.182** | -1.741 (0) |
| Belgium | 1.8 | 0.166 | 5.411 | 1.00 | -4.735 | -4.044*** (0) |
| Canada | 0.8 | 0.134 | 11.808*** | 6.00 | -4.652*** | -1.799 (1) |
| Chile | 2.4 | 4.099 | 0.695 | 7.00 | -0.439 | -6.645*** (0) |
| Colombia | 5.0 | 4.989 | 0.572 | 4.00 | -2.546 | -5.032*** (2) |
| Czechia | 0.9 | 0.715 | 9.659** | 7.00 | -4.901*** | -1.796 (2) |
| Finland | 1.1 | 0.238 | 8.857** | 7.00 | -4.238** | -1.893 (3) |
| France | 4.2 | 0.319 | 1.324 | 1.00 | -2.210 | -2.972** (1) |
| Germany | 3.3 | 0.128 | 2.828 | 0.00 | 0.253 | -1.448 (1) |
| Greece | 0.1 | 3.509 | 5.568 | 6.00 | -3.015 | -4.208*** (0) |
| Hungary | 0.1 | 1.934 | 12.673*** | 6.00 | -4.155** | -3.602** (0) |
| Ireland | 4.2 | 2.267 | 1.789 | 5.00 | -3.414 | -5.283*** (0) |
| Italy | 0.9 | 0.138 | 4.568 | 1.00 | -3.694 | -3.362** (0) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Japan | 1.3 | 0.032 | 6.164 | 4.00 | -3.712 | -1.487 (0) |
| Korea | 0.1 | 0.239 | 12.846*** | 3.00 | -4.788*** | -1.214 (0) |
| Luxembourg | 1.0 | 1.577 | 6.305 | 2.00 | -3.921 | -3.016** (0) |
| Mexico | 1.6 | 1.553 | 12.100*** | 6.00 | -4.961*** | -7.400*** (0) |
| Netherlands | 3.0 | 0.158 | 4.286 | 4.00 | -1.881 | -2.381 (2) |
| New Zealand | 1.9 | 1.024 | 9.565** | 7.00 | -3.588** | -3.372** (3) |
| Norway | 2.0 | 0.423 | 4.437 | 6.00 | -1.972 | -1.901 (2) |
| Poland | 0.8 | 3.172 | 6.219 | 6.00 | -3.831 | -6.658*** (0) |
| Portugal | 0.1 | 1.469 | 6.627* | 1.00 | -3.714* | -0.506 (2) |
| Slovak Republic | 4.9 | 3.305 | 6.461* | 6.00 | -2.564 | -7.563*** (0) |
| Slovenia | 1.5 | 5.053 | 10.499*** | 7.00 | -4.982*** | -5.355*** (0) |
| Spain | 0.6 | 0.440 | 2.977 | 7.00 | -2.299 | -1.349 (1) |
| Sweden | 0.8 | 0.150 | 16.572*** | 7.00 | -4.686*** | -1.579 (1) |
| Switzerland | 4.0 | 0.205 | 2.284 | 1.00 | -1.427 | -1.151 (0) |
| Türkiye | 0.9 | 2.958 | 10.026** | 7.00 | -4.349** | -3.846*** (0) |
| UK | 1.0 | 0.035 | 6.224 | 5.00 | -3.247 | -0.900 (2) |
| United States | 1.4 | 0.028 | 11.118*** | 2.00 | -4.265*** | -2.263 (2) |

**Note:** ***,**,* indicate statistical significance at 99%, 95%, and 90% confidence levels. The Akaike information criterion was used in the ADF unit root test. The maximum lag length was taken as 3. The value in parentheses indicates the optimum lag length.

When determining whether trigonometric terms are meaningful, the F-test statistic is examined. If this test statistic is greater than the critical values in the Enders and Lee (2012) table, the FADF test statistic of the Fourier unit root test is examined. Otherwise, the stationarity of the series is determined by examining the ADF unit root test statistic. Table 2 shows that the Fourier function is statistically significant in 15 countries, and convergence is observed in 14 of these 15 countries. There are 16 countries where the trigonometric terms are not significant. When the stationarity of the series is examined for these countries, the series are stationary in 9 countries. Therefore, convergence is also observed in these 9 countries. Convergence was determined in 23 of the 31 countries considered in total. Based on the results of the model with only the constant, convergence is found in Austria, Australia, Belgium, Chile, Czech Republic, Colombia, Canada, Finland, France, Greece, Hungary, Italy, Ireland, Korea, Luxembourg, Mexico, New Zealand, Portugal, Poland, Slovenia, Sweden, Türkiye and the United States. The shares of environmental technology-related patents in these countries' total patents converge to the OECD average. The results of the constant and trend models are presented in Table 3.

**Table 3.** Unit Root Test Results (Constant+Trend)

| Country | Freq. | Min KKT | F Test | Optimum lag | FADF Test Stat. | ADF Test Stat. |
|---|---|---|---|---|---|---|
| Australia | 2.2 | 0.174 | 10.873** | 5.00 | 1.903 | -2.480 (0) |
| Austria | 2.8 | 0.171 | 3.463 | 1.00 | -2.624 | -2.683 (0) |
| Belgium | 1.6 | 0.151 | 14.520*** | 7.00 | -4.193** | -4.236** (0) |
| Canada | 2.2 | 0.131 | 5.283 | 7.00 | -0.443 | -3.933** (0) |
| Chile | 2.1 | 3.393 | 1.822 | 7.00 | -1.910 | -6.859*** (0) |
| Colombia | 5.0 | 4.950 | 0.4391 | 4.00 | -2.572 | -4.949*** (2) |
| Czechia | 0.1 | 0.674 | 11.811** | 7.00 | -5.165*** | -3.875** (0) |
| Finland | 0.1 | 0.225 | 11.418** | 7.00 | -4.574** | -3.696** (0) |
| France | 0.1 | 0.276 | 9.599** | 3.00 | -3.970* | -3.157 (1) |
| Germany | 0.1 | 0.106 | 1.210 | 2.00 | -2.981 | -3.948** (2) |
| Greece | 1.7 | 2.550 | 5.022 | 2.00 | -5.097 | -6.883*** (0) |
| Hungary | 4.1 | 1.578 | 2.146 | 7.00 | -0.565 | -5.579*** (0) |
| Ireland | 4.2 | 2.265 | 1.736 | 5.00 | -3.416 | -5.205***(0) |
| Italy | 1.4 | 0.129 | 10.028** | 6.00 | -4.375** | -3.258* (0) |
| Japan | 1.4 | 0.031 | 6.319 | 4.00 | -3.795 | -1.507 (0) |
| Korea | 5.0 | 0.164 | 1.901 | 7.00 | -1.399 | -4.220** (2) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Luxembourg | 0.1 | 1.469 | 5.242 | 2.00 | -4.165 | -3.788** (2) |
| Mexico | 1.3 | 1.506 | 16.438*** | 6.00 | -5.524*** | -7.279*** (0) |
| Netherlands | 3.0 | 0.155 | 4.321 | 7.00 | 0.111 | -1.894 (0) |
| New Zealand | 1.9 | 0.964 | 16.219*** | 7.00 | -4.867*** | -3.431* (3) |
| Norway | 2.0 | 0.415 | 5.575 | 5.00 | -3.558 | -1.705 (2) |
| Poland | 0.4 | 3.151 | 2.946 | 6.00 | -3.844 | -6.780*** (0) |
| Portugal | 3.6 | 1.166 | 3.801 | 2.00 | -3.295 | -6.741*** (0) |
| Slovak Republic | 4.9 | 3.154 | 5.861 | 6.00 | -2.343 | -5.565*** (1) |
| Slovenia | 1.5 | 4.896 | 10.970** | 7.00 | -4.899*** | -5.352*** (0) |
| Spain | 1.6 | 0.378 | 16.972*** | 6.00 | -5.903*** | -3.779** (0) |
| Sweden | 0.1 | 0.141 | 4.652 | 1.00 | -3.805 | -1.307 (0) |
| Switzerland | 0.8 | 0.151 | 7.319 | 5.00 | -3.983 | -2.132 (0) |
| Türkiye | 4.9 | 2.704 | 4.206 | 7.00 | -2.423 | -4.802*** (0) |
| UK | 1.4 | 0.033 | 10.683** | 7.00 | -3.575 | -2.269 (0) |
| United States | 1.4 | 0.026 | 13.707*** | 3.00 | -4.465** | -2.237 (2) |

**Note:** ***,**,* indicate statistical significance at 99%, 95%, and 90% confidence levels. The Akaike information criterion was used in the ADF unit root test. The maximum lag length was taken as 3. The value in parentheses indicates the optimum lag length.

The model results, including the constant and trend, are presented in Table 3. These results show that the Fourier function is statistically significant in 12 countries. In 84% of the 12 countries where trigonometric terms are significant, the series are stationary. In other words, convergence is present in 10 countries. There are 19 countries where trigonometric terms are not significant. For these countries, the ADF unit root test should be examined. When examining the stationarity of these series, it is observed that the series are stationary in 13 countries. Therefore, convergence is also present in these countries. In total, convergence is found in 23 of the 31 countries. These 23 countries are: Belgium, Chile, Canada, Czech Republic, Colombia, France, Finland, Greece, Germany, Hungary, Italy, Ireland, Korea, Luxembourg, Mexico, New Zealand, Portugal, Poland, Slovenia, Slovakia, Spain, Türkiye and the USA. The share of environmental technology-related patents in these countries' total patents converges to the OECD average.

## 6. Result

Although solutions have been found to halve emissions by 2030, significant and rapid technological innovations are needed to achieve net zero emissions by 2050. Considering the point made by WIPO, the importance of patented technologies becomes apparent. This study examines whether there is convergence of environment-related patents with the OECD country group average.

According to the results of the analysis conducted with the fractional Fourier unit root test, there is environmental patent convergence in 23 of the 31 countries included in the analysis. There is no convergence in environmental patents in 25% of the countries studied. Convergence is found in the majority of countries. Studies using carbon emissions as an indicator include Lee and Chang (2008), which found convergence in 7 out of 21 OECD countries, and Barassi et al. (2011) found convergence in 13 out of 18 OECD countries; Solarin (2019), using ecological footprint as an indicator, found convergence in 13 out of 27 OECD countries. Solarin et al. (2018) found convergence in 14 out of 27 OECD countries in terms of renewable energy convergence. Solarin et al. (2025) found convergence in 15 out of 22 countries, including EU and UK countries, for the indicator of the number of patents per million people for environmental technologies. For the indicator "total number of patents applied for in environmental technologies per billion real GDP (using 2015 US dollar prices)," convergence was found in 14 countries. When the results of these studies are evaluated, it is generally observed that convergence does not exist in all OECD countries. Furthermore, it can be said that the results vary depending on the indicator examined for convergence. Generally, convergence is observed in approximately 50% of the countries included in the OECD country group. The findings of our study indicate that convergence exists in 75% of the 31 countries included in the analysis. Therefore, it can be said that the OECD country group is in a better position to develop common policies regarding environmental patents compared to other indicators. Considering the results of convergence analysis, inferences can be drawn as to whether countries should pursue common or separate policies. In countries where convergence exists, it is recommended that common policies be pursued. However, in countries where convergence does not exist, pursuing a common policy may not yield positive results. It may be beneficial for these countries to develop specific policies in addition to common policies.

If the share of environmental patent applications in total patents is stable, then stochastic convergence exists in that country. This means that shocks occurring in countries where convergence exists will have a temporary or transient effect. Second, for countries where the ratio of environmental patents to total patents converges toward the average, the past trend of environmental patents can be used to predict future environmental patents. However, for countries where the share of environmental patents in total patents does not exhibit stochastic convergence toward the average, it is not recommended to use the past behavior of environmental patents to predict future environmental patents.

The United Nations Framework Convention, the Kyoto Protocol, and the Paris Climate Agreement demonstrate that climate change is a global challenge. While highlighting that each country must take different actions in addition to global efforts, it also shows that developed countries have a greater responsibility. Developed countries should support efforts to mitigate the effects of climate change by both reducing their emissions and providing technological, financial, and technical support to developing countries. It would be particularly beneficial for countries at the forefront of climate change-related technological research to prioritize their patented technologies. These technologies could be commercialized by other developed countries. The green technologies developed countries possess to combat climate change should also be transferred to developing countries. On the other hand, the establishment of global or regional special funds for the commercialization of advanced technological innovations that have been patented but are not yet used in the sector could accelerate the green transformation process. Additionally, supporting the transfer of technology from developed countries to developing or underdeveloped countries could contribute to achieving the net-zero emissions target.

In future studies, the results can be compared by examining the environmental patent indicator, club convergence, and different convergence analyses. Convergence analyses related to environmental patents can also be performed using different unit root tests. On the other hand, convergence analyses using different indicators focused on technology and innovation can be presented to contribute to the identification of areas where countries should pursue common policies. Convergence analyses using technological indicators can also be performed for different country groups.

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