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ARTICLE

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Eco-innovation and environmental sustainability in Germany: An empirical approach with smooth structural shifts

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Abstract

Germany has set an ambitious goal of meeting the recommendations of COP-26 and reducing its carbon intensity to zero by 2045. Germany is a leader in environmental patents after the United States, Japan, and South Korea, and the environmental implications of Germany's leadership in eco-innovation hold important clues for achieving net zero goals. In particular, the European Union is one of the global communities making the greatest efforts to combat emissions, and the success of the leading role of environmental patents in this Union in reducing CO_2 emissions is an important research topic for scholars. Therefore, this study investigates the impact of environmental patents on CO_2 emissions under the environmental Kuznets curve (EKC) hypothesis in Germany. To this end, the study applies Bayer–Hanck and Fourier ADL approaches from 1970 to 2019. The main findings do not confirm the EKC hypothesis, while environmental patents play an active role in CO_2 reduction. Based on these outcomes, Germany should consider a long-term green policy to decouple economic growth and emissions. At the same time, German policy should promote the development and application of environmental patents to achieve the net zero targets for 2045.

KEYWORDS
CO_2 emissions, eco-innovation, environmental patents, environmental quality, sustainable development

1 | INTRODUCTION

The goal of sustainable development is to meet current needs without compromising the resources of future generations. Governments have adopted sustainable growth policies by transforming their production and consumption patterns (Fernández et al., 2018). At this point in time, energy consumption is constrained as the majority of energy needs continue to be met by fossil fuels. In particular, underdeveloped and developing countries rely on the use of natural resources for their economic growth. The use of fossil fuels causes pollution, which is an obstacle to sustainable development. In this context, governments are seeking solutions to climate change through international negotiations under the UNFCCC. One of the most ambitious solutions under the Paris Agreement is to achieve the net zero target by 2050. At the COP27 conference in Sharm-e-Sheikh in 2022, several governments set specific targets to achieve net zero emissions by 2050 and shared their roadmap (UNFCCC, 2022). Another ambitious goal is the sustainable development goals (SDGs), which cover many areas, such as climate change, green energy, institutional quality, and human rights.

Policymakers and researchers are working hard to make the SDGs a success. Various researchers are studying the determinants of ecological issues under the EKC hypothesis and proposing solutions to prevent pollution within the scope of the SDGs. The term EKC was first used by Panayotou (1993). An inverted U-shaped curve was first demonstrated by Grossman and Krueger (1991). The researchers divided the environmental effects of income into three categories: Scale effects, composition effects, and technique effects. The scale effect states that high production requires more energy and causes pollution. The technique effect, on the contrary, implies that with technological development, dirty energy technologies are abandoned. With green technologies, clean and efficient production can be achieved through environmental innovation. In other words: According to the technique effect, there is a close link between technological innovations and environmental conditions.

The theoretical basis of the relationship between technological progress and the environment is based on endogenous growth models and the EKC hypothesis. Endogenous growth models assume that economic growth is achieved through technological progress, research and development (R&D) expenditures, and increase in patents. The reflection of this growth on environmental quality can be analyzed using the EKC hypothesis. If technological progress supports environmentally friendly energy sources and production technologies, the increase in the number of patents can theoretically limit environmental degradation.

Although environmental innovations have a low return on investment in the short term, they have a favorable impact on productivity in the long term by reducing environmental costs and leading to resource efficiency (Aldieri et al., 2021). There is a broad consensus in the literature that environmental innovation could be a strategic tool to achieve the SDGs, increase energy efficiency, and reduce environmental risks (Mongo et al., 2021). Technology also improves environmental degradation by promoting environmental innovation and reducing energy consumption, primarily through energy efficiency. Many studies have found that environmental innovations improve environmental sustainability (Lin & Zhu, 2019; Mensah et al., 2019). Environmental patents are significant for environmental innovation because they promote clean technologies and help reduce CO_2 emissions. They are also considered an essential policy tool to improve environmental sustainability by integrating renewable energy into the transportation, industrial, and construction sectors (Oyebanji et al., 2022). In addition, while clean technologies are promoted to improve environmental quality, they should not undermine economic growth (Aggeri, 1999). Therefore, governments are trying to take initiatives to promote the creation and adoption of environmental technologies (De Jong et al., 2016). In this way, patents on environmental technologies could support the decoupling between economic expansion and ecological pollution.

The other positive impact of technological development is the reduction of environmental degradation through renewable energy (Zhang et al., 2017). Technological advances and patents in renewable energy could play a crucial role in improving ecological conditions (Lin & Zhu, 2019). Numerous studies confirm that advances in low-carbon technologies and energy efficiency reduce environmental degradation (Frondel et al., 2010; Gerlagh, 2007; Kartal, Pata, Destek, & Caglar, 2023; Levenda et al., 2021; Yang & Li, 2017; Zhao et al., 2013). Environmental innovation is one of the most important actors for the expansion of renewable energy technologies, as it reduces the production costs of renewable energy and improves energy efficiency (Bayer et al., 2013). Developed countries have more advantages in achieving sustainable development thanks to their advanced financial systems, infrastructures, technologies, R&D activities, and patent incentives. As an industrialized country, Germany also invests significantly in environmental patents. Do these investments contribute to reducing CO_2 emissions and achieving the SDGs? This study attempts to answer this research question.

Germany is a major player that signed the Paris Agreement in 2015. With this agreement, Germany set a binding CO_2 reduction target for 2030.[1] This target was revised in 2021 with a new climate law. The new law increased the emission reduction target for 2030 to 65% and set it at 88% for 2040. Finally, the net zero emission target for 2050 was extended to 2045 (Climate Change Act, 2021). Germany is a strong economic actor with its advanced economy, financial infrastructure, technology capacity, and investments in green energy. In this way, it can use environmental patents as a powerful policy instrument to achieve sustainable SDGs. According to the report of the Berlin Energy Transition Dialogue (2022), the share of renewable energy in final energy consumption is 41% in the electricity sector, 16.5% in the heating sector, and 6.8% in transport. The goal is to boost renewable energy consumption to 80% by 2030 and to build a carbon-neutral economy by 2045. Germany's robust renewable energy generation infrastructure facilitates climate change mitigation strategies, reduces energy dependence, and spurs ecological innovation.

Germany has set an ambitious net zero target by 2045. However, it does not seem easy to achieve even the earlier targets with current measures (Edenhofer et al., 2021). This is because the recent rise in energy prices and energy security issues undermine net zero targets by steering governments toward cheap and domestic fossil fuels. In addition, the recent global inflation problem has forced governments to raise interest rates, risking recession. To fight inflation, governments tend to resort to cheap and traditional energy sources. To avoid using imported gas for electricity generation, the government has already proposed to reactivate coal-fired power plants (Lan et al., 2022). Against this background, it is assumed that an additional emissions gap could arise in Germany to meet the net zero target by 2045. The motivation of this study is to discuss how environmental patents can be used as a policy tool to close this emission gap in Germany.

Figure 1 shows the trend of environmental patents and CO_2 emissions in Germany during the period under study. While in 1972, the share of environmental patents was 9.76%; in 2005, it was 9.72%. In 2006, the percentage of environmental patents in total patents in Germany exceeded 10% for the first time and has been 13%–14% since then. Per capita CO_2 emissions in Germany decreased by 17.5% in the 35 years from 1970 to 2006. In the 13 years between 2006 and 2019, CO_2 emissions fell by 23% from 10.8 to 8.5 tons. Do environmental patents play a role in this success in reducing CO_2 emissions? This study explores the validity of this research question for Germany.

The study makes two major contributions to the literature, both methodologically and conceptually. (i) The study analyzes the effect of environmental patents on CO_2 emissions for the first time using time series methods for Germany. The study covers the period between 1970 and 2019 to investigate the impact of environmental patents on environmental quality and to account for structural changes during this period, such as globalization and the global financial crisis. The study chooses this sample because Germany is one of the leading countries in the European Union. Therefore, German environmental policies can affect other countries in the region and support international efforts to solve environmental degradation. (ii) The study aims to obtain robust results by using Bayer–Hanck and Fourier ADL cointegration methods. There are several cointegration tests in the literature, each of which can provide different results on long-term relationships. The Bayer–Hanck approach eliminates this complexity by combining four different cointegration tests. On the contrary, the Fourier ADL approach allows the analysis of the cointegration relationship considering smooth structural shifts. Patents can be affected by various problems such as ecological degradation, economic crises, and natural disasters, and the trends of these series can change due to these

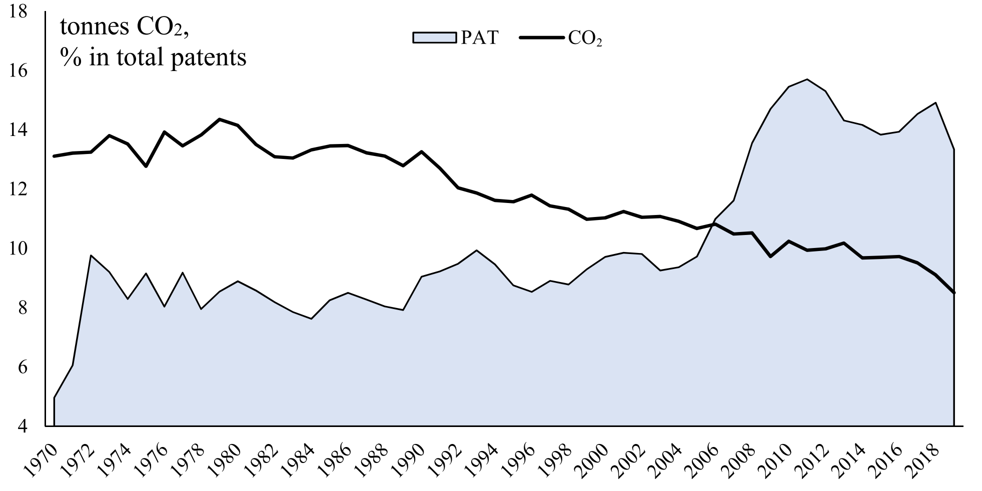

FIGURE 1 Environmental patents and CO_2 emissions in Germany from 1970 to 2019. *Source*: OECD (2022) and Our World in Data (2022).

events. The Fourier ADL test minimizes the errors in the conclusions about the cointegration relationships because these changes are not taken into account. With these aspects, the study provides a new field of discussion for the environmental economics by analyzing the relationships between environmental patents and CO_2 emissions using the Fourier trigonometric terms. The study also added Fourier trigonometric terms to the empirical model to consider structural changes over the sample period. In this way, there is no need for additional tests to observe structural breaks. (iii) To the best knowledge, this is the first paper that examines the impact of environmental patents in Germany. A seminal analysis of the influence of patents on environmental technologies in Germany represents a significant value to the literature. Finally, empirical results and policy implications should guide German policymakers and make them aware of the potential risks and opportunities of environmental patents. The results also contribute to the literature by revealing additional strategies for closing potential emissions gaps and achieving SDGs.

The study consists of five parts. In the first part, the effects of environmental patents on ecological pollution and the EKC hypothesis are discussed theoretically, and information on Germany's net zero targets is provided. The second part presents the literature review. The third part introduces the methodology, while the fourth part reports the empirical results. The last part discusses the empirical findings and suggests policy implications.

2 | LITERATURE REVIEW

Many studies address the validity of the EKC hypothesis while examining the determinants of environmental degradation (Erdogan et al., 2020, 2022; Magazzino, Gallegati, & Giri, 2023; Pata, 2018; Pata & Yurtkuran, 2023; Tenaw & Beyene, 2021; Wang, Yang, & Li, 2023). Some studies also focus on environmental role of fossil fuels (Kartal, Pata, Depren, & Depren, 2023), income inequality (Ozturk et al., 2022), environmental taxes (Sharif et al., 2023), urbanization (Magazzino, Mele, Morelli, & Schneider, 2021), electricity consumption (Matar et al., 2023), natural resources (Demir et al., 2023), globalization (Pata, Erdogan, & Ozkan, 2023), governance (Magazzino, Adedoyin, et al., 2023), foreign direct investment (Seker et al., 2015), renewable energy (Magazzino et al., 2022), trade openness (Ertugrul et al., 2016), geopolitical risk (Pata, Kartal, & Zafar, 2023), and digital economy (Wang, Sun, et al., 2023). There are also studies investigating the effects of environmental pollutants such as carbon emissions on health expenditures (see, e.g., Ecevit et al., 2023). However, a few studies have focused on Germany with time series analyzes, examining the EKC hypothesis (Egli, 2002, 2004; Zambrano-Monserrate & Fernandez, 2017). Table 1 presents studies that have empirically analyzed the determinants of ecological degradation in Germany.

The above seven studies analyzed environmental factors in Germany using different time-series methods, but none focused on the role of environmental patents. Moreover, there is no consensus on the validity of the EKC for Germany. Two of the seven studies do not cover the EKC hypothesis, two support its validity, and three appear to oppose it. As long as the technology is environmentally friendly, the technical impacts mentioned in the EKC hypothesis could have a positive impact on the environment (Pham et al., 2020; Shahbaz et al., 2018). This study mainly focuses on the impact of environmental patents on CO_2 emissions in Germany. Therefore, the next step is to discuss the studies that examine the impact of patents on CO_2 emissions in the literature.

Wang et al. (2012) argued that the increase in technology patents could reduce pollution in 30 Chinese provinces, as the development of lower carbon technologies leads to lower CO_2 emissions. Yii and Geetha (2017) concluded that patents mitigate CO_2 emissions in Malaysia. Mensah et al. (2018) recommend imposing high taxes on energy-intensive industries to encourage R&D investment in environmental technologies. They also suggest promoting patents and investing in less polluting technologies in 28 countries. Hashmi and Alam (2019) found that green patents decrease CO_2 emissions in OECD countries. According to the study, targeting green technologies instead of non-green technologies could be crucial to lowering emissions. Mensah et al. (2019) suggested that OECD countries should promote brands and patents to motivate the development of green products. Cheng et al. (2021) emphasized that environmental patents reduce CO_2 emissions asymmetrically across all quantiles in 35 OECD countries. Adebayo et al. (2023) revealed the importance of environmental patents for CO_2 reduction in BRICS countries. Mongo et al. (2021) noted that patent-related environmental technologies lower CO_2 emissions in 15 European Union (EU) countries. Shobande and Ogbeifun (2023) reported that patents help predict, monitor, and mitigate the negative impacts of CO_2 emissions. Jiang and Khattak (2023) emphasized that the increasing number of environmental patents and their share in total patents reduce CO_2 emissions in South Korea. Ahmad et al. (2023), Li and Zhang (2023), Liu et al. (2023), Kirikkaleli et al. (2023), and Yang et al. (2023) also noted that green patents help to the reduction of CO_2 in China.

TABLE 1 Studies on the determinants of ecological degradation in Germany.

Author (s)	Period	Method	Related findings	EKC
Egli (2002)	1966–1998	Regression analysis	EKC is not valid for CO_2, nitrodioxide, and sulfur dioxide.	X
Egli (2004)	1966–1999	Regression analysis	EKC is not valid for CO_2 and methane.	X
Zambrano-Monserrate and Fernandez (2017)	1970–2012	ARDL	GDP has an ∩-shaped link with nitrous oxide.	√
Magazzino, Mele, Schneider, and Shahbaz (2021)	1990–2018	Quantum model	GDP plays a key role in determining CO_2	None
Ibrahim et al. (2022)	1990–2020	NARDL	Internet use reduces CO_2 emissions	None
Liu et al. (2022)	1890–2015	Kink regression	GDP increases CO_2	X
Pata and Hizarci (2022)	1968–2017	Fourier ARDL	GDP has an ∩-shaped link with ecological footprint pressure index	√
Pata, Kartal, Erdogan, and Sarkodie (2023)	1974–2018	Fourier ADL	∩-shaped link between GDP and CO_2	√

Note: √ shows validity of the EKC, while X denotes invalidity.
Abbreviation: NARDL, nonlinear ARDL.

In a departure from the consensus on the environmental role of eco-patents, Cheng et al. (2019) determined that environmental patents trigger CO_2 emissions in BRIICS countries. Tobelmann and Wendler (2020) noted that patents may not be sufficient to reduce CO_2 emissions in EU-27 countries. Li et al. (2021) concluded that patents have an inverted U-shaped link with CO_2 emissions in 30 Chinese provinces. Ullah et al. (2021) revealed that shocks from patents have an insignificant effect on CO_2 emissions in Pakistan. Alatas (2022) found that environmental patents have an insignificant impact on transport-related CO_2 in the EU-15 countries. Yildirim et al. (2022) reported that patents have a decreasing influence on CO_2 emissions in the medium regime, but this effect becomes positive in the high regime for 32 OECD countries. Song et al. (2023) found that technological innovation and economic growth support green energy generation in Australia.

From the above studies, it appears that researchers do not fully agree on the environmental impact of patents. Moreover, no study to date has investigated whether environmental patents effectively reduce CO_2 emissions in Germany, which is a research gap in this literature. This study aims to contribute to the existing literature by applying the Fourier ADL method and examining the impact of environmental patents on pollution reduction in Germany.

3 | MODEL, DATA, AND METHODOLOGY

3.1 | Model and data

The study explores the influence of environmental patents on CO_2 emissions under the EKC hypothesis in Germany. In this context, the Fourier ADL approach is applied to Equation (1).

$$LCO_{2it} = \beta_1 LPAT_{it} + \beta_2 LGDP_{it} + \beta_3 LGDP_{it}^2 + \varepsilon_{it}, \qquad (1)$$

where LCO_2 denotes carbon emissions, LPAT indicates patents on environmental technologies, and LGDP represents economic growth over the period 1970–2019. The data period is chosen according to the available period of PAT, which ends in 2019. Therefore, the study includes 50 observations for each variable.

In recent studies, CO_2 emissions stand for environmental sustainability (Nurgazina et al., 2022; Pata & Kartal, 2022). Following Ulucak, Khan, et al. (2020) and Oyebanji et al. (2022), environmental innovation is proxied by patents on environmental technologies. Based on the modelling of Cheng et al. (2019) and Li et al. (2021), this study examines the carbon mitigation effects of environmental patents under the EKC hypothesis. The natural logarithmic form is used for all series whose sources, units, and information are listed in Table 2.

Figure 2 shows the time course of the variables involved in the analysis. The decrease in LCO_2 from 2.6 to 2.1 shows that Germany has significantly reduced its CO_2 emissions. GDP shows an increasing trend. On the contrary, environmental patents remained stable between 1970 and 2003 but have increased significantly since the 2000s, graphically illustrating the importance Germany attaches to the development of environmental patents.

Table 3 demonstrates that PAT has the lowest minimum value. GDP is the variable with the highest volatility. All three series have a normal distribution with skewness close to 0, kurtosis close to 2, and Jarque-Bera values with p-values greater than 0.10. Furthermore, the correlation matrix in Table 3 shows that there is a strong positive link between GDP and CO_2, and a negative strong relationship between CO_2 and PAT.

TABLE 2 Data description.

Series	Unit	Symbol	Reference
Carbon emissions	Per capita, tonnes	CO_2	Our World in Data (2022)
Economic growth	Per capita, constant, 2015$	GDP	World Bank (2022)
Patents on environmental technologies	% in total	PAT	OECD (2022)

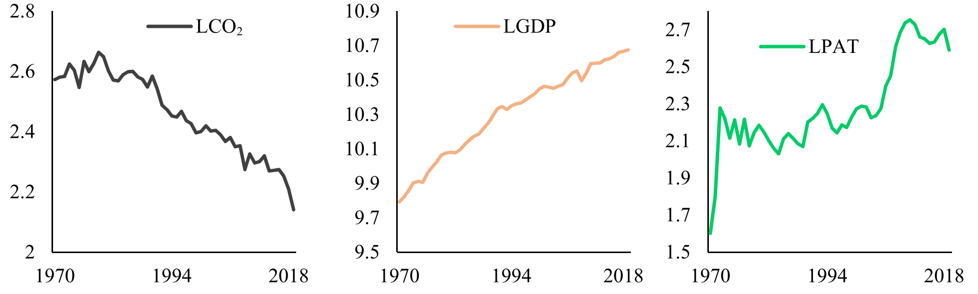

FIGURE 2 Time paths of the logarithm variables.

TABLE 3 Descriptive stats.

	LCO_2	LGDP	LPAT
Std. Dev.	0.136	0.256	0.252
Mean	2.460	10.306	2.287
Median	2.459	10.355	2.222
Skewness	−0.357	−0.375	0.216
Kurtosis	2.001	1.973	2.987
Maximum	2.663	10.675	2.753
Minimum	2.140	9.792	1.601
Jarque-Bera	3.142	3.369	0.389
Probability	0.207	0.185	0.823
Observations	50	50	50
LCO_2	1	0.804	−0.820
LGDP	0.804	1	−0.904
LPAT	−0.820	−0.904	1

After defining the working variables and examining their graphs, the empirical process follows in Figure 3. In the second step, the unit roots of the series are explored with ADF and FADF unit root tests. The appropriate lag length for the BH cointegration test is determined in the third step. The long-run relationships are analyzed with BH and FADL cointegration tests in the fourth and fifth steps. In the sixth step, the FMOLS estimator, including smooth structural shifts, is applied, and elasticities are estimated to test the validity of EKC and the environmental effects of patents. In the final stage, a robustness check is performed using the DOLS method.

The study uses FADF and FADL methods to effectively account for the smooth structural shifts that Germany has undergone. Econometric methods using Fourier transforms can better capture breaks and provide more effective results. Therefore, this study aims to accurately determine the impact of environmental patents on CO_2 emissions by incorporating Fourier approximations into FMOLS and DOLS estimators.

3.2 | Methodology

This section provides information on the FADL and BH tests used for cointegration analysis. The study applies these methods using econometric programs, such as Stata-17 and Eviews-12. The FADL cointegration test was proposed by Banerjee et al. (2017), which accounts for structural breaks in time series data without specifying break dates. By

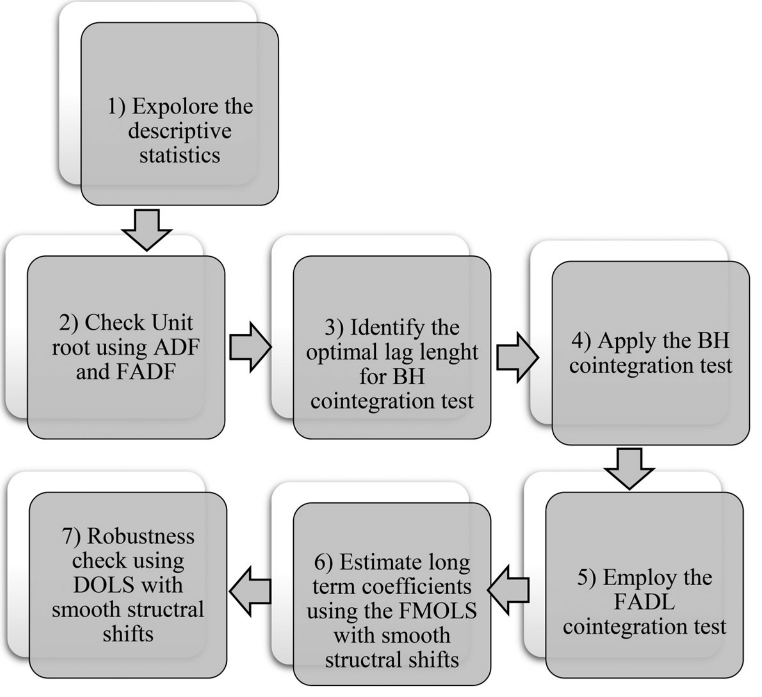

FIGURE 3 Empirical framework.

using Fourier approximations, this test minimizes the problems caused by adding too many dummy variables. Equation (2) defines a deterministic component using the FADL approach.

$$d(t) = a_0 + \Sigma_{k=1}^{q} a_{1,2} \sin\left(\frac{2\pi kt}{T}\right) + \Sigma_{k=1}^{q} a_{2,k} \cos\left(\frac{2\pi kt}{T}\right), q \le \frac{T}{2}, \tag{2}$$

where α_0 is the deterministic term with a constant and linear trend, k is the number of specific frequencies, q is the number of frequencies, and T is the total observation. Banerjee et al. (2017) explain the testing procedure through the conditional model in Equation (3).

$$\Delta y_t = d(t) + \beta_1 y_{t-1} + \gamma' x_{t-1} + \varphi' \Delta x_t + u_t. \tag{3}$$

In Equation (3), β_1 is tested using a t-test to examine the validity of the null and alternative hypothesis for cointegration, which can be defined as in Equation (4):

$$H_0 : \beta_1 = 0 \,(\text{no cointegration}), H_{\text{alternative}} : \beta_1 \neq 0 \,(\text{cointegration}) \tag{4}$$

After comparing the empirical statistics with the critical values, the existence of cointegration is established if the FADL test statistic is greater in absolute value than the critical values.

On the contrary, Bayer and Hanck (2013) suggested the BH cointegration test to avoid false inferences that may arise from different cointegration tests giving different results. This test can be performed by combining the probability values of the tests of Engle and Granger (1987) (EG), Johansen (1988) (JOH), Boswijk (1994) (BO), and

Banerjee et al. (1998) (BDM). The two test statistics calculated in the application of the BH are presented in Equation (5):

$$EG-JOH=-2[\ln(pEG)+\ln(pJOH)],$$

$$EG-JOH-BO-BDM=-2[\ln(pEG)+\ln(pJOH)+\ln(pBO)+\ln(pBDM)], \quad (5)$$

where *p* stands for the probability values.

4 | EMPIRICAL RESULTS

The necessity of many cointegration tests is that the series must be I (1). Therefore, the first stage of the study examines the stochastic properties of CO_2, GDP, and PAT, and the outcomes of the unit root tests are shown in Table 4.

The FADF test statistics in Table 3 show that all three series contain a unit root. The F-statistics are lower than the critical value of 5% of 9.140 suggested by Enders and Lee (2012). Becker et al. (2006) stated that using traditional tests instead of a Fourier-based stationarity test is more appropriate when the F-statistics are insignificant. Therefore, the study also employs the traditional augmented Dickey–Fuller (Dickey & Fuller, 1981) (ADF) unit root test, which depicts that the series are nonstationary at the level of values. All three series are stationary at the first difference I(1), and for these reasons, it is appropriate to use cointegration tests such as Bayer and Hanck (2013) and Fourier ADL. The former provides inferences about the long-term relationships by considering four different cointegration tests, and the latter helps determine robust results by including smooth structural shifts in the cointegration relationships. The appropriate lag length is first determined for the BH test based on vector autoregression, as shown in Table 5.

Using the information criteria, AIC shows that the optimal lag length is 4, while it should be 1 according to FPE, SIC, and HQ. When the information criteria are evaluated as a whole, it can be seen that the optimal lag for the BH test is "1." Therefore, the BH test is performed with a lag length of "1,", and Table 6 reports the findings.

The BH test indicates a long-term link between CO_2, PAT, and GDP. The EG-J test was statistically significant at 1% and the EG-J-BO-BDM test at 5%. The BH test, which combines four different cointegration tests, confirms cointegration among series. Then, the FADL test is applied to determine whether the cointegration link change in the presence of structural breaks. Table 7 illustrates FADL cointegration results.

The FADL test statistic (4.951) is greater in absolute value than the critical value of 1% (4.750), so CO_2, GDP, and PAT are cointegrated. Having demonstrated a long-run relationship with FARDL and BH tests, FMOLS by Phillips and Hansen (1990) and DOLS by Stock and Watson (1993) are used to analyze the validity of EKC for Germany and the impact of eco-innovation on CO_2 reduction. Table 8 presents the FMOLS findings.

The FMOLS test shows that the EKC cannot be supported for Germany. These findings are incompatible with Ma et al. (2021), and Pata and Hizarci (2022). For Germany, a U-shaped relationship exists between income and CO_2

TABLE 4 FADF and ADF unit root test results.

					ADF	
	Frequency	FADFI (0)	I (1)	*F*-stat.	I (0)	I (1)
LCO_2	4	0.496	−3.957**	3.328	0.747	−8.516*
LGDP	2	−3.725	−6.966*	1.773	−2.488	−6.448*
LPAT	1	−2.519	−3.786**	3.450	−2.065	−6.365*

Note: * and ** illustrate the significance of the stationarity at the 1% and 5% levels, respectively.

TABLE 5 Optimal lag selection for the BH test.

Lag	LogL	LR	FPE	AIC	SIC	HQ
0	217.562	NA	1.09e−09	−9.285	−9.126	−9.225
1	450.245	414.782	**8.86e−14***	−18.706	**−17.911***	**−18.408***
2	457.442	11.577	1.32e−13	−18.323	−16.892	−17.787
3	478.747	30.568*	1.10e−13	−18.554	−16.487	−17.779
4	499.426	26.073	9.72e−14	**−18.757***	−16.054	−17.745

*Bold values show the selected optimal lag.

TABLE 6 Results of the BH cointegration test.

Tests	EG-J	EG-J-BO-BDM
Test stat.	17.931*	22.853**
1% CV	16.259	31.169
5% CV	10.636	20.486

Note: * and ** show the significance at the 5% level.

TABLE 7 FADL approach results.

Optimal frequency	4	Critical values		
FADL (1,2,2,1)		10%	%5	%1
Test stat.	−4.951*	−3.650	−4.030	−4.750

*Shows the significance at 1% level.

TABLE 8 FMOLS results.

Variable	Coefficient	Std. dev	*t*-Statistic	Prob.
lnGDP	−1.789**	0.872	−2.051	0.046
lnGDP^2	0.079***	0.046	1.694	0.097
lnPAT	−0.316*	0.075	−4.168	0.000
C	45.777**	19.967	2.292	0.026
SSIN	−0.010	0.014	−0.725	0.472
CCOS	−0.019	0.014	−1.296	0.201
Diagnostic check	R^2	0.913	Jarque-Bera	0.888

Note: *, **, and *** show the significance at 1%, 5%, and 10% levels, respectively.

emissions. Germany reduces its CO_2 emissions as income increases, but beyond a certain point, this reverses. The EKC is not applicable and is consistent with Egli (2004) and Liu et al. (2022) for Germany. Regarding environmental innovation, a 1% increase in environment-related patents reduces CO_2 emissions by 0.31%. In contrast to Cheng et al. (2019), the environmentally friendly role of PAT has been supported by Ulucak, Danish, and Kassouri (2020), Cheng et al. (2021), Mongo et al. (2021), and Xin et al. (2021). Finally, the robustness of these findings is controlled using the DOLS method, and the outcomes are listed in Table 9.

The DOLS results confirm the FMOLS. Differently, SSIN is statistically significant. The FMOLS and DOLS estimators consider possible structural changes in the series using trigonometric Fourier terms (SSIN & CCOS).

According to the DOLS estimator, a 1% increase in PAT lowers CO_2 emissions by 0.30%. Figure 4 summarizes the empirical results.

In terms of environmental PAT, the empirical findings show resemblances with the studies of Adebayo et al. (2023), Ahmad et al. (2023), Liu et al. (2023), and Yang et al. (2023), who highlighted the eco-friendly role of PAT. However, Cheng et al. (2019) found that environmental patents may not be helpful in lowering ecological degradation. Studies that determine that environmental PAT increases environmental quality generally explain these findings through energy efficiency and renewable energy production, while studies with negative results refer to additional energy demand and fossil carbon-based emissions. For Germany, the environmental role of PAT is valid, and the expansion of environmental technologies contributes to carbon neutrality goals through the improved use of clean energy.

German environmental patents are critical to the development of technologies for energy transmission and distribution and pollution reduction in transportation and industry (Mongo et al., 2021). The rise in new patents supports advancing carbon capture and storage technologies, green buildings, and environmental chemistry. In addition, the development of environmental patents is popularizing energy-saving and energy-efficient applications. Patents can also help make renewable energy investments more effective and less costly. With such practices, the German government can make economic development more cost-effective. In other words, policymakers can achieve a

TABLE 9 Robustness check with DOLS.

Variable	Coefficient	Std. dev	*t*-Statistic	Prob.
lnGDP	−1.598**	0.519	−3.079	0.005
lnGDP^2	0.070**	0.028	2.448	0.022
lnPAT	−0.304*	0.047	−6.452	0.000
C	41.197*	11.810	3.488	0.001
SSIN	−0.014**	0.006	−2.204	0.037
CCOS	0.007	0.007	1.075	0.292
Diagnostic check	R^2	0.975	Jarque-Bera	0.365

Note: * and ** show the significance at 1% and 5% levels, respectively.

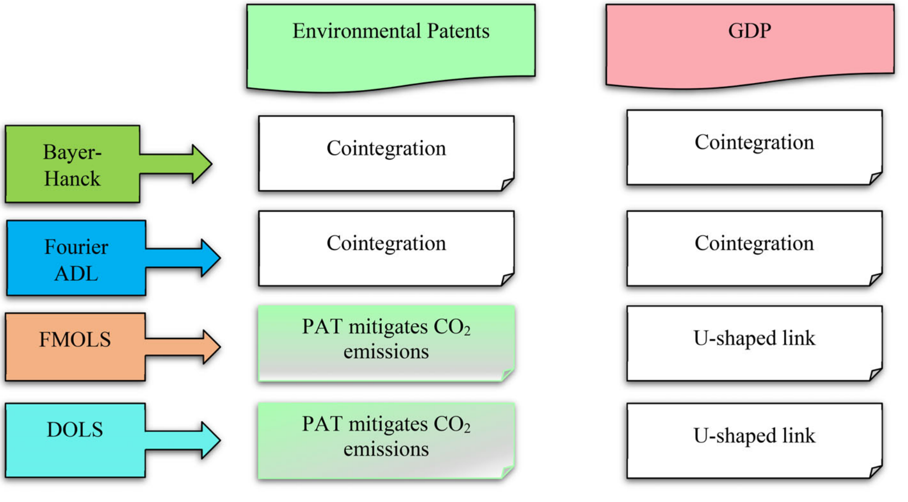

FIGURE 4 Summary of the cointegration and estimation results.

double benefit by simultaneously providing environmental and economic benefits to German society through the diffusion of environmental patents. In this context, increasing German government spending on environmental patents can be an important policy tool.

The invalidity of the EKC shows that economic growth still has a negative interaction with the environment. Therefore, Germany could not protect the environment while promoting economic growth. In other words, there is no economic growth without environmental pollution. For this reason, it is concluded that the phenomenon of decoupling, which has been frequently discussed in the literature recently, does not apply to Germany. Therefore, Germany should accelerate its policies to build a low-carbon economy and develop additional sustainability strategies.

5 | CONCLUSION AND POLICY IMPLICATIONS

EU countries are taking essential steps in the fight against climate change and are playing a leading role worldwide. To join the EU, countries must meet specific environmental standards as well as economic conditions. EU countries aim to bring their CO_2 emissions by 55% below 1990 levels by 2030 and achieve carbon neutrality by 2050 (European Commissions, 2023). In this context, Europe should implement common economic and environmental policies to achieve the EU's net zero targets. It also needs a strong institutional capacity to build consensus on climate conflicts and enforce long-term policies (Dubash, 2021). As an important EU member, Germany is a critical player in sustainable development and environmental policies. Therefore, German environmental policies to achieve environmental sustainability could lead to creative destruction in other countries. This work analyzes the influence of green patents on ecological quality in Germany. The empirical results show that environmental patents enhance environmental sustainability by lowering CO_2 emissions in Germany. Moreover, a U-shaped relationship exists between income and CO_2 emissions, and the EKC does not hold for Germany. These results suggest that there is no decoupling between economic expansion and environmental degradation in Germany. In other words, although Germany is a massive user of renewable energy, its economic structure is not yet conducive to decoupling. Therefore, green policies need to be promoted more vigorously to achieve the SDGs and the net zero targets for 2045.

Technological developments in environmental sustainability can reduce environmental degradation by increasing energy efficiency (Wurlod & Noailly, 2018). Our empirical findings reveal that patents on environmental technologies can mitigate CO_2 emissions. The empirical outcomes are consistent with theoretical expectations and point to significant policy recommendations, particularly in the area of environmental regulations that directly contribute to environmental quality (Liu et al., 2018; Wang & Shen, 2016). Environmental regulations can lead to emission reductions through technological innovation. This process stimulates the growth of environmental patents. However, the introduction of new products and technologies through patents and innovations can increase energy use by creating additional demand for the products. Therefore, the German government should combine innovation and environmental strategies to achieve the goal of net zero emissions by 2050.

Eco-innovation is effective in many areas, such as environmental pollution, drought, energy efficiency, and ecological footprint. Therefore, many countries are promoting technologies to mitigate climate change (Urbaniec et al., 2021). This study asserts that environmental patents should be considered as a policy tool to combat climate change and achieve environmental sustainability, as they are essential components of eco-innovation. In addition to legal regulations and government spending strategies, they also contribute to the creation of tax incentives for eco-innovation (Ferreira et al., 2020). Undoubtedly, environmental patents will become more effective as countries move toward a low-carbon economy. As market-based environmental regulations have proven effective in improving eco-efficiency (Ren et al., 2018), Cheng et al. (2019) called for legislative regulations on environmental technologies to improve environmental quality worldwide.

Environmental patents are an effective advance for the use and diffusion of renewable energy. Therefore, policymakers should create various incentives to increase the number of green patent applications. Companies that develop renewable energy patents should receive benefits from the German government in the form of tax exemptions, low-interest loans, and employment advantages. As the number of environmental patent applications increases and technology diffusion accelerates, the use of clean energy in society will increase and it will be easier to achieve carbon reduction and zero balance goals.

The main consequence of the study show that environmental patents are a critical environmental policy instrument for Germany and that their promotion should be continued. Patent development can focus on different energy sources, such as renewable, nuclear, and fossil fuels. Germany has recently tended to return to fossil fuels due to the negative impact of energy prices from COVID-19 and Ukraine-Russia (Reuters, 2022). Olaf Scholz, the German Chancellor, justified the decision to bring coal and oil-fired power plants back online by stating that "to cushion the impact of energy shortages because of Russia's war in Ukraine is only temporary."[2] Based on this viewpoint, this study suggests a future study for researchers. A study that examines how economic and political turmoil after 2020 undermines net zero 2050 targets can make an essential contribution to the literature. In this context, the research can be directed to the environmental policies of Germany and EU countries by discussing that Germany can help reduce CO_2 emissions by focusing on developing patents for what type of energy source.

The limitation of this study is that the subcomponents of environmental patents were not considered because each type of environmental patent could have different environmental consequences. Therefore, future studies can focus on the environmental impacts of subcomponents of PAT. This would help authorities apply specific economic and environmental policies.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTES

[1] Federal Climate Change Act (2019, Section 3). https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Gesetze/ksg_final_en_bf.pdf (Accessed 28 December 2022).

[2] See at https://markets.businessinsider.com/news/commodities/germanys-scholz-says-switch-back-to-coal-and-oil-temporary-11537007.

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