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Technological changes and carbon neutrality targets in European countries: A sustainability approach with Fourier approximations

Ugur Korkut Pata [a,b,c,*], Mustafa Tevfik Kartal [b,c,d], Shahriyar Mukhtarov [e,f,g]

[a] Osmaniye Korkut Ata University Department of Economics, Osmaniye, Türkiye
[b] Lebanese American University Adnan Kassar School of Business, Beirut, Lebanon
[c] Azerbaijan State University of Economics (UNEC) Clinic of Economics, Baku, Azerbaijan
[d] Borsa Istanbul Strategic Planning, Financial Reporting, and Investor Relations Directorate, İstanbul, Türkiye
[e] Vistula University, Faculty of Business and International Relations, Warsaw, Poland
[f] Azerbaijan State University of Economics (UNEC) Empirical Research Center, Baku, Azerbaijan
[g] Khazar University, Department of Economics and Management, Baku, Azerbaijan

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ABSTRACT

The diffusion of net-zero technologies is highly recommended as European Union (EU) countries aim for carbon neutrality by 2050. Germany, France, and the Netherlands are EU countries that invest heavily in environmental patents, and the relationship between patent development and carbon reduction in these countries provides important clues for carbon neutrality goals. Therefore, this study examines the effects of technological change (environmental patents), human capital, and income on carbon (CO_2) emissions for three EU member countries over the period 1974–2019 under the Environmental Kuznets Curve (EKC) hypothesis. For this purpose, the study applies the Fourier-ADL approach and various time series estimators. The results of the study show that the EKC hypothesis is valid for EU countries and that human capital contributes to carbon reduction. Moreover, environmental patents contribute to CO_2 mitigation in Germany, but environmental patents do not have a significant effect on emission reduction in France and the Netherlands. These results suggest that France and the Netherlands should invest more in environmental patents and, like Germany, benefit from the CO_2 reduction effects of environmental patents.

1. Introduction

Effective environmental policy instruments are a prerequisite for implementing the Sustainable Development Goals (SDGs). To achieve the SDGs, countries are making efforts to reduce carbon emissions through various policy instruments. These efforts have been and continue to be put on the agenda at the international level with various commitments under the Kyoto Protocol, the Paris Conference, and the Conference of the Parties. Among these commitments is the environmentally friendly use of technological progress to reduce CO_2 emissions. To this end, countries aim to contribute to the fight against climate change by supporting technological progress and patents that increase energy efficiency, promote the use of renewable energy, and ensure minimization of CO_2 emissions.

Countries have in the past and still today neglected environmental conditions for their economic purposes. When a society reaches a certain level of income and wealth, it wants to live in a better environment. In this context, the increase in GDP is one of the most important factors affecting ecological conditions. According to Grossman and Krueger (1991), an augment in GDP increases ecological degradation with the scale effect in the first stage of economic development, but then reduces environmental pollutants such as carbon emissions thanks to the composition and technique effect. The technique effect is closely related to technological progress and environmental patents.

The rising CO_2 emissions are largely anthropogenic, and therefore it is in the hands of humanity to prevent climate change. One of these ways for humanity is to develop the possibility of environmental intervention through technological progress. Today, technological progress is faster and more diverse than ever before. Patents are an important indicator of technological development and innovation (Popp, 2006), and the number of environmental patents has increased significantly, especially since the 1970s (Su and Moaniba, 2017). Patents are often used to protect high-technology products with economic value (Hussin and

* Corresponding at: Osmaniye Korkut Ata University Department of Economics, Osmaniye, Türkiye.
E-mail addresses: korkutpata@osmaniye.edu.tr (U.K. Pata), s.mukhtarov@vistula.edu.pl, smukhtarov@khazar.org (S. Mukhtarov).

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Acronyms

Abbreviations

CV	Critical Value
DOLS	Dynamic OLS
EF	Ecological Footprint
EKC	Environmental Kuznets Curve
EPO	European Patent Office
EU	European Union
FADL	Fourier Autoregressive Distributive Lag
FMOLS	Fully Modified OLS
GCC	Gulf Cooperation Council
LM	Lagrange Multiplier
OECD	Organisation for Economic Co-operation and Development
SDGs	Sustainable Development Goals
TY	Toda Yamamoto
US	United States
ZA	Zivot and Andrews

Dependent variable

CO_2	Carbon Dioxide

Independent variables

GDP	Gross Domestic Product
HC	Human Capital
EPAT	Patents on Environmental Technologies

Aroua, 2020). Patents grant exclusive rights to an invention that provides a new way or technical solution for a particular activity (Ben Youssef, 2020). Since patents symbolize research and development activities, they are closely linked to the state of technological development (Cho and Sohn, 2018). Technological progress can increase carbon emissions by increasing intensive production through the emission of negative externalities, and on the contrary, it can help prevent environmental degradation by promoting the development of clean energy technologies (Li et al., 2021). The second effect, called the Technique effect, implies that technological progress is a beneficial factor for environmental conditions.

Technological development is one of the key factors affecting CO_2 emissions, as it includes various carbon reduction technologies (Lin and Ma, 2022a). As for technological advancement, the diffusion of environmental patents can support carbon reduction by increasing energy efficiency (Cheng et al., 2019). Technological innovation includes new patents, and thanks to these patents, the production process can be designed (Cheng et al., 2021a). Carrying out the production process in a cleaner and carbon-free manner with new patents contributes to carbon reduction. Patents are also associated with human capital. If individuals with high human capital do not use technological advancements, it may not bring the necessary benefits to society. For example, if there are not enough skilled personnel to effectively use the patents developed for carbon capture technology, these patents and technological advances may not have the necessary positive impact on the environment. Therefore, human capital and patents together can help reduce carbon emissions. In addition, the development of human capital can accelerate the transition to a better ecosystem with people who support the expansion of eco- friendly technologies and have a desire to expand the use of clean energy. Therefore, human capital is an important environmental determinant, just like environmental patents.

Nowadays, environmental patents are becoming a necessity for a better ecosystem. Many countries around the world are investing significantly in the development of environmental patents. Among these groups of countries, the countries of the European Union (EU) occupy an important place. EU countries attach great importance to the development of environmental patents in the context of raising environmental standards and achieving the SDGs. Germany, France, and the Netherlands are among the countries with the most patent applications among the EU countries (EPO, 2023). In Germany, environmental patents account for 13.3 % of total patents in 2019, 12.5 % in France, and 9.53 % in the Netherlands (OECD, 2023). These data show that 1 in 10 patents in EU countries relate to the environment. Whether this rate contributes to carbon neutrality goals is important to ensure the interplay between technological progress and carbon reduction. Therefore, this study aims to examine the influence of environmental patents on carbon mitigation and net zero targets in Germany, France, and the Netherlands. The time course of environmental patents in the three relevant countries over the last 50 years is shown in Fig. 1.

Fig. 1 illustrates that Germany has made progress in environmental patents up to the year 2000, while France and the Netherlands have not. In the roughly 30-year period between 1974 and 2000, the share of Dutch environmental patents in total patents averaged 6 %. In France, the share of environmental patents in total patents, which was 10 % between 1974 and 1980, declined to 6–7 % in the 1990s. Especially since 2005, this share has increased significantly in all three countries. In 2011, the share of German environmental patents in total patents reached 15.7 %. France, on the other hand, reached its historic high in 2012 with an environmental patent ratio of 14.3 %. By 2019, environmental patent rates had declined in all three countries, falling below 10 % in the Netherlands. Nevertheless, the share of environmental patents in total patents has increased in all three countries over the 50-year period. Is this increase effective in reducing carbon emissions? This study attempts to find an answer to this question. Fig. 2 shows carbon emissions in the three EU countries.

Fig. 2 shows that Germany, France, and the Netherlands have made significant progress in reducing CO_2 emissions over the 50-year period. Germany has reduced its CO_2 emissions, which were 13.51 tons per capita in 1974, by 37 % to 8.5 tons in 2019. France, on the other hand, has reduced its per capita CO_2 emissions by 50 % during this period. The Netherlands' CO_2 reduction rate is 25 % and its per capita CO_2 is higher than the other two countries.

There may be an interaction between CO_2 reductions by EU countries and technological progress over time. To date, no study has examined the impact of environmental patents on CO_2 emissions of EU member states. In this respect, the study contributes to the existing literature. Another contribution of the study is that it examines the relationships between environmental patents and CO_2 emissions using Fourier-based econometric methods. The evolution of patents can change significantly over time and be affected by structural changes. In the study, potential

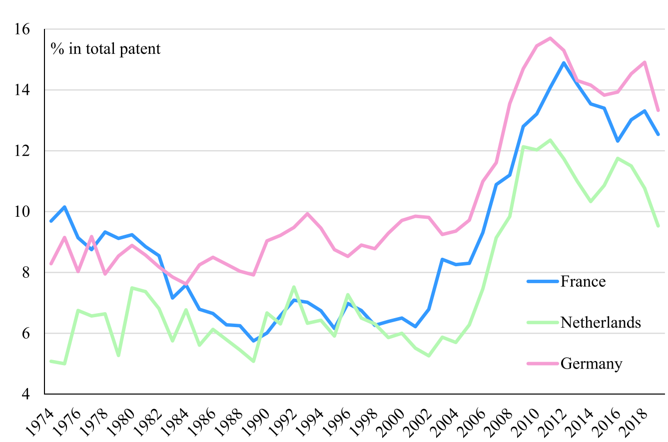

Fig. 1. Patents on environmental technologies.
Source: OECD (2023).

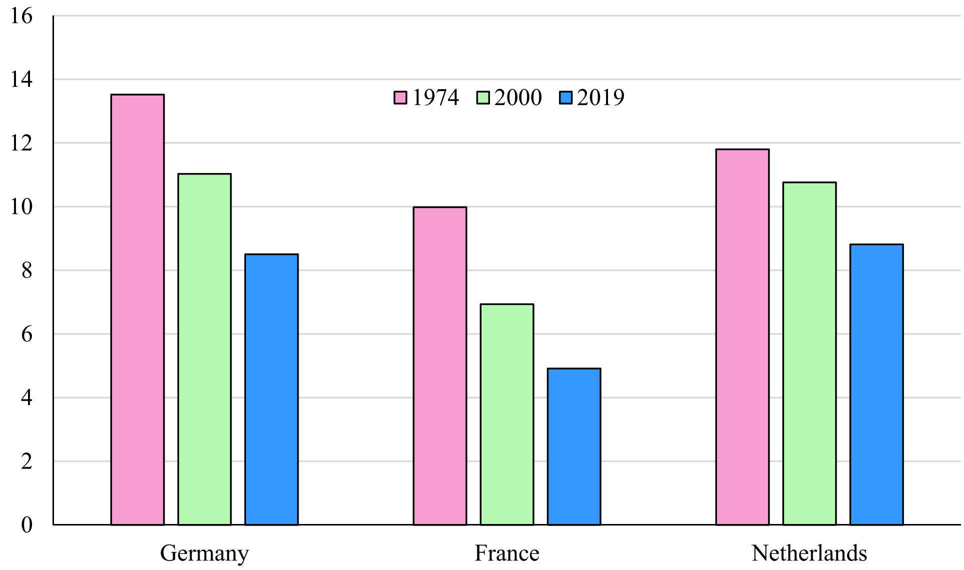

Fig. 2. CO_2 emissions in EU countries.
Source: Our World in Data (2023).

smooth shifts are accounted for using Fourier functions. Thus, the study makes a methodological and comprehensible contribution to the existing literature.

In this study, which consists of five sections, the second section presents the literature on the relationship between patents and the environment. The third section introduces the data and methodology, and the fourth section discusses the findings. The last section concludes the study and provides suggestions for future research.

Following the introduction section, the second part reviews the literature; the third section explains the methods; the fourth part presents the results, and the fifth section concludes.

2. Literature review

2.1. EKC studies

In the literature, since the leading study by Grossman and Krueger in 1991, there have been a number of studies examining the critical effect of income on ecological progress. Some research have explored the influence of GDP on the environment using linear modeling (Adebayo et al., 2023; Kartal et al., 2023; Sharif et al., 2023), while others have used quadratic models within the context of EKC. Under the EKC hypothesis approach, scholars have investigated whether there is a threshold effect of income level on the environment. Some of the studies have confirmed the EKC hypothesis (e.g., Gyamfi et al., 2023 for Asian nations; Pata et al., 2023a for Germany; Pata et al., 2023b for technologically advanced countries; Uche et al., 2023a for India). Other studies have demonstrated the invalidity of the EKC hypothesis (e.g., Li et al., 2021 for China; Barut et al., 2023 for the Fragile Five countries; Voumik et al., 2023 for ten countries) and shown that increases in income are detrimental to the environment.

The EKC has also been analyzed for EU countries, but there is no consensus on its validity. Boluk and Mert (2014), for example, find that the EKC does not apply to 16 EU countries. Balsalobre-Lorente et al. (2021) support the validity of the EKC for five EU countries. Bekun et al. (2021) emphasize that the EKC is valid for 27 EU countries. Frodyma et al. (2022) stated that EKC is not valid for 28 EU countries. Pata and Yurtkuran (2023) state that EKC is valid for Switzerland and Denmark, but not for Sweden and Austria. There is no consensus on whether the EKC is valid, suggesting that additional research is needed to determine carbon neutrality in EU countries.

2.2. Human capital and CO_2 emissions

In addition to income, some other studies have considered human capital as an important determinant of the environment. For instance, Pata and Caglar (2021) report that human capital helps to reduce CO_2 emissions and the EF. Lin and Ma (2022b) report that technological progress in China can help reduce CO_2 emissions if human capital reaches a certain level. Mahmood et al. (2022) find that human capital mitigates CO_2 emissions and the EF for 28 OECD countries. Yao et al. (2020) note that human capital has sociological and ecological benefits for 20 OECD countries. Lee and Zhao (2023) emphasized the CO_2 reducing role of human capital for 96 countries. Lin et al. (2023) state that human capital supports China's sustainable development. On the contrary, Shu et al. (2023) emphasize that there is a positive relationship between CO_2 emissions and human capital for China. Uche et al. (2023b) focus on BRICS countries and define that human capital has no impact on CO_2 emissions. Pata et al. (2023c) analyze the case of the US and find that human capital promotes environmental quality. Wang et al. (2023) conclude that human capital was the driving force in CO_2 reduction after the EKC turning point for 208 countries.

Many studies examining the impact of human capital on the environment have shifted to its environmental benefits, but the number of studies for EU countries is limited. This is another research gap.

2.3. Patents and CO_2 emissions

Recent studies have also considered the environmental impact of patents as an indicator of technological progress. Hashmi and Alam (2019) conclude that an increase in eco-friendly patents curbs CO_2 emissions in OECD countries. However, Töbelmann and Wendler (2020) determine that environmental innovations do not contribute to CO_2 reduction in the 26 EU countries. Cheng et al. (2021a) examine BRIICS countries and define that environmental patent development causes an insignificant increase in per capita CO_2 emissions. Khurshid et al. (2022) find that eco-patents curb CO_2 emissions in Europe. Li et al. (2021) study China and conclude that patents have an inverted U-shape with CO_2 emissions. Mongo et al. (2021) study EU-15 countries and determine that environmental innovations have a lowering effect on CO_2 emissions. Abbasi et al. (2022) find that patents can contribute to CO2 reduction in Pakistan. Oyebanji et al. (2022) analyze Spain and state that environmental patents promote environmental sustainability.

Ghorbal and Ben Youssef (2023) find that patents derived from foreign investment contribute to CO_2 minimization in South Korea. Su et al. (2023) note that the environmental impact of granted patents can be positive or negative. They show that in the US, total patents can increase CO_2 emissions by increasing energy consumption, while environmentally friendly patents can help carbon neutrality. Uche et al. (2023b) examine the environment-related technological innovations represented by trademark applications by focusing on BRICS countries and find that they have a regressive effect on CO_2 emissions. Yang et al. (2023) state that patents related to alternative energy mitigate CO_2 emissions.

2.4. Evaluation of the literature

Looking at the literature in terms of patent scope, it is noticeable that many studies have focused on the leading CO_2 emitting countries (e.g., China, India, GCC countries). However, EU countries have rarely been analyzed in the literature (Pata et al., 2023a for Germany). Moreover, studies examining the influence of environmental patents on CO_2 emissions are relatively limited. Previous studies generally consider the totality of patents in a country. These patents can also support the development of technologies that promote the use of fossil fuels. Therefore, it is a more accurate approach to assess the impact of environmental patents on CO_2 emissions.

Although there are many studies in the literature that address environmental quality and carbon neutrality goals, there is still a need for new research because previous studies have not considered environmental patents, nor have they focused on leading countries with higher levels of patents. Considering these points, this study considers environmental patents in carbon neutrality research by focusing on leading EU countries. The study contributes to the existing literature by examining, for the first time for EU countries, the impact of environmental patents on CO_2 emissions using Fourier-based methods.

3. Methods

3.1. Data and model

The study investigates the effects of environmental patents on carbon neutrality targets under the EKC hypothesis in leading European countries. Since environmental patent data are available until 2019, the time period is set to 1974–2019. The study utilizes Eq. (1) as the basis for empirical modeling.

$$lnCO_{2_t} = \delta_0 + \delta_1 \ln GDP_t + \delta_2 lnGDP_t^2 + \delta_3 \ln HC + \delta_4 \ln EPAT + \varepsilon_t \tag{1}$$

where ln is the logarithm, $\delta_{1\ \text{to}\ 4}$ are the long term coefficients, and ε_t is the error term. CO_2 denotes CO_2 emissions, GDP shows gross domestic product, HC indicates human capital, and EPAT illustrates environmental patents. Table 1 provides detailed information about the variables and data sources.

Table 1
Details of the variables.

Variable	Symbol	Unit	Reference
CO_2 emissions	CO_2	Per capita (tons)	Our World in Data (2023)
Gross domestic product	GDP	Per capita (constant 2017$)	Penn World Table (2023)
Human capital	HC	An index based on education and skills	Penn World Table (2023)
Patents on environmental technologies	EPAT	% in total patent	OECD (2023)

3.2. Methodology

The study follows a five-stage prediction strategy that is presented in Fig. 3. In the first stage, the variables' descriptive statistics are examined. Later, the study tests the stochastic properties of the variables using the approaches of Zivot and Andrews (1992) [ZA] and Fourier LM by Enders and Lee (2012). For cointegration analysis, the study uses the FADL procedure of Banerjee et al. (2017). Then, the long-run coefficients are calculated using the FMOLS of Phillips and Hansen (1990).

In the final stage, DOLS of Stock and Watson (1993) is used for robustness. In these calculations, the study accounts for smooth structural changes by adding Fourier transforms to the estimators. Thus, the study aims to make effective predictions of the effects of environmental patents on CO_2 emissions in the countries.

3.3. Fourier-based approaches

The Fourier transforms proposed by Gallant (1981) have been widely used in various econometric approaches over the last twenty years. For example, Becker et al. (2006) consider Fourier approximations in stationarity analysis. Nazlioglu et al. (2016) apply Fourier transforms to the TY causality test. Cheng et al. (2021b) develop the Fourier TY causality test to account for quantiles.

Researchers prefer Fourier transforms because they can account for smooth structural breaks. The trigonometric terms sine and cosine of Fourier functions allow smooth structural changes to be accounted for in empirical modeling. In this way, prediction errors can be eliminated that may arise because of dummy variables.

This study uses Fourier LM for unit root analysis and FADL for cointegration analysis. The first stage of the Fourier LM approach can be formulated by Eq. (2).

$$\Delta y_t = \sigma_0 + \sigma_1 \Delta sin\left(\frac{2\pi kt}{T}\right) + \sigma_2 \Delta cos\left(\frac{2\pi kt}{T}\right) + e_t \tag{2}$$

where Δ illustrates the difference operator, sin shows sinne, cos denotes cosine, k represents the optimal frequency, t symbolizes the time trend, and e_t exemplifies the error term. In the second stage, the coefficients σ_0, σ_1, and σ_2 are revised as in Eq. (3) and the series are detrended as follows:

$$\widetilde{S}_t = y_t - \widetilde{\forall} - \widetilde{\sigma}_0 - \widetilde{\sigma}_1 sin\left(\frac{2\pi kt}{T}\right) - \widetilde{\sigma}_2 cos\left(\frac{2\pi kt}{T}\right), t = 2, \ldots 3\ldots, 4\ldots, T \tag{3}$$

In Eq. (3), $\widetilde{\forall} = y_1 - \widetilde{\sigma}_0 - \widetilde{\sigma}_1 sin\left(\frac{2\pi kt}{T}\right) - \widetilde{\sigma}_2 cos\left(\frac{2\pi kt}{T}\right)$, where y_1 denotes the first observation of the series. In the final stage, the null hypothesis that the Fourier LM test has a unit root is analyzed for the detrended series by Eq. (4).

$$\Delta y_t = \delta \widetilde{S}_{t-1} + \beta_0 + \beta_1 sin\left(\frac{2\pi kt}{T}\right) + \beta_2 cos\left(\frac{2\pi kt}{T}\right) + v_t \tag{4}$$

If the null hypothesis of the τ_{LM} test statistic (H_0: $\delta = 0$) is rejected, it can be stated that the series under study is stationary with smooth shifts.

The study employs the FADL approach for cointegration analysis. Banerjee et al. (2017) suggest the use of the FADL test by adding Fourier approximations to the ADL model to minimize the prediction errors caused by using too many dummies. Eq. (5) shows the time-varying intercept (d(t)) for the FADL test.

$$d(t) = \mu_0 + \Sigma_{k=1}^{j} \mu_{1,2} sin\left(\frac{2\pi kt}{T}\right) + \Sigma_{k=1}^{j} \mu_{2,k} cos\left(\frac{2\pi kt}{T}\right), j \leq \frac{T}{2} \tag{5}$$

where j shows the lag length, and π illustrates the pi-value as 3.14. The frequency (k) values in Eq. (5) can be determined fractionally (i.e., k = 0.1…, 0.2…, 4.9 to 5) following Christopoulos and León-Ledesma (2010). Taking $d(t)$ into account, the cointegration model can be formulated as in Eq. (6):

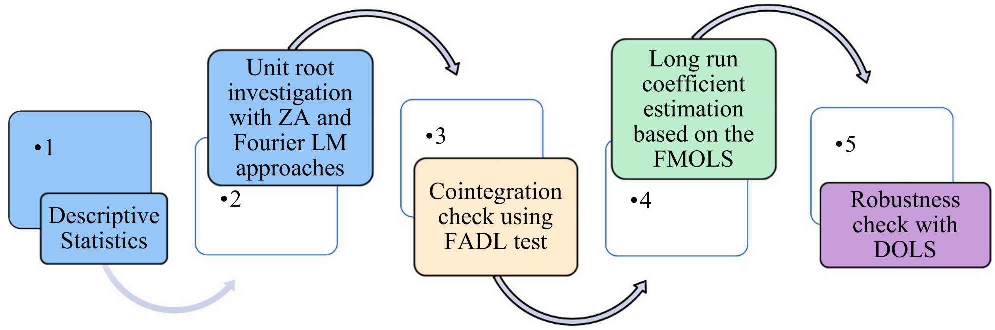

Fig. 3. Methodological flowchart.

$$\Delta y_t = \mu_0 + \Sigma_{k=1}^{j}\mu_{1,2} sin\left(\frac{2\pi kt}{T}\right) + \Sigma_{k=1}^{j}\mu_{2,k} cos\left(\frac{2\pi kt}{T}\right) + \varnothing y_{t-1} + \gamma^{'} x_{t-1} + \varphi^{'}\Delta x_t + z_t \quad (6)$$

The null hypothesis is analyzed as H_0: $\varnothing = 0$ (no cointegration). Following the suggestion of Banerjee et al. (2017), the t-statistic in Eq. (7) is employed for the cointegration analysis.

$$t_{ADL}^{F} = \frac{\widetilde{\varnothing}}{standart\ error\ (\widetilde{\varnothing})} \quad (7)$$

If the calculated test statistic (t_{ADL}^{F}) is greater in absolute value than the critical values, which may vary with frequency, the null hypothesis is rejected. Thus, the cointegration relationship among the series under study is proven.

4. Empirical results

Table 2 shows the descriptive statistics of the variables. For Germany, HC and EPAT are not normally distributed; in contrast, CO_2 and GDP have a normal distribution. The variable with the highest volatility is GDP, and the variable with the lowest volatility is HC. In France, the CO_2, GDP, HC, and EPAT series are normally distributed. In France, the most volatile variable is EPAT, while HC has the lowest volatility. Similarly, EPAT and GDP have high volatility in the Netherlands. In other words, environmental patents can be affected by external shocks and exhibit large changes over time in France and the Netherlands. Environmental patents in Germany follow a more stable trend than in France and the Netherlands.

Next, the study applies ZA and Fourier LM unit root tests to analyze whether all variables have a unit root (i.e., I(1)), which is a prerequisite for the FADL test. Table 3 presents the results of the ZA unit root test.

The results of the ZA unit root test indicate that HC for the Netherlands is stationary at the 10 % significance level. The first difference of HC for the Netherlands is stationary at the 1 % significance level. All other series contain unit roots at levels for all three countries, while these series are stationary at their first differences. The break date for environmental patents in Germany is due to the global crisis of 2008. This global crisis affected environmental patents in Germany. Patents in the Netherlands were affected by the early recession of the 2000s, which also affected the European Union. Both cases show that environmental patents are sensitive to economic shocks.

ZA unit root test reveals the structural break date endogenously and ignores smooth changes. For this reason, the study uses the Fourier LM test and outcomes are shown in Table 4.

The results of the Fourier LM test show that all series are stationary at first difference I(1). Therefore, it is appropriate to test long-term relationships with the FADL cointegration test. Table 5 presents the cointegration results for the countries.

Table 2
Descriptive statistics.

	$lnCO_2$	lnGDP	lnHC	lnEPAT
Germany				
Mean	2.449	10.379	1.238	2.314
Median	2.442	10.418	1.257	2.226
Maximum	2.663	10.845	1.301	2.753
Minimum	2.140	9.810	1.104	2.030
Std.Dev.	0.136	0.339	0.060	0.230
Skewness	−0.222	−0.195	−0.785	0.760
Kurtosis	1.983	1.617	2.344	2.042
Jarque − Bera	2.359	3.956	5.555	6.185
Probability	0.307	0.138	0.062	0.045
France				
Mean	1.939	10.333	1.045	2.164
Median	1.934	10.293	1.050	2.138
Maximum	2.300	10.686	1.172	2.700
Minimum	1.591	9.951	0.884	1.749
Std.Dev.	0.190	0.236	0.077	0.293
Skewness	0.247	0.012	−0.295	0.379
Kurtosis	2.666	1.499	2.231	1.769
Jarque − Bera	0.681	4.317	1.801	4.006
Probability	0.711	0.115	0.406	0.134
Netherlands				
Mean	2.366	10.479	1.123	1.980
Median	2.384	10.444	1.128	1.887
Maximum	2.589	10.925	1.222	2.513
Minimum	2.176	10.042	1.004	1.609
Std.Dev.	0.088	0.325	0.063	0.284
Skewness	0.042	0.078	−0.203	0.667
Kurtosis	2.706	1.347	1.909	2.048
Jarque − Bera	0.178	5.279	2.596	5.154
Probability	0.914	0.071	0.272	0.075

Table 3
ZA unit root test results.

	I(0)	lag	I(1)	lag
Germany				
$lnCO_2$	−4.483 [1991]	0	−10.223*	0
lnGDP	−2.685 [1988]	0	−7.456*	0
lnHC	−2.945 [1985]	1	−8.004*	0
lnEPAT	−3.743 [2008]	1	−8.354*	0
France				
$lnCO_2$	−2.841 [1981]	0	−9.173*	0
lnGDP	−4.373 [1997]	1	−6.176*	0
lnHC	−4.724 [1991]	2	−6.146*	0
lnEPAT	−2.912 [1983]	0	−7.805*	0
Netherlands				
$lnCO_2$	−4.249 [1989]	1	−10.249*	0
lnGDP	−2.454 [2005]	0	−6.994*	0
lnHC	−4.900 [2001]***	1	−7.204*	0
lnEPAT	−4.398 [2000]	6	−5.370**	1

Note: ***, **, and * denote 10 %, 5 %, and 1 % significance, respectively. [] includes break dates.

Table 4
Fourier LM unit root test results.

	I(0)	Frequency &lag	I(1)	Frequency &lag
Germany				
$\ln CO_2$	−2.712	k = 2, lag = 5	−5.254*	k = 5, lag = 0
lnGDP	−2.772	k = 1, lag = 0	−5.880*	k = 5, lag = 0
lnHC	−0.941	k = 5, lag = 1	−5.484*	k = 4, lag = 1
lnEPAT	−2.713	k = 1, lag = 4	−4.509*	k = 3, lag = 0
France				
$\ln CO_2$	−2.964	k = 1, lag = 4	−4.850**	k = 1, lag = 1
lnGDP	−2.432	k = 1, lag = 1	−4.947**	k = 1, lag = 1
lnHC	−1.610	k = 3, lag = 1	−6.431*	k = 1, lag = 0
lnEPAT	−2.985	k = 1, lag = 3	−5.229**	k = 1, lag = 1
Netherlands				
$\ln CO_2$	−3.796	k = 1, lag = 3	−7.362*	k = 3, lag = 0
lnGDP	−3.121	k = 1, lag = 0	−5.524*	k = 1, lag = 0
lnHC	−0.861	k = 5, lag = 1	−5.214**	k = 1, lag = 0
lnEPAT	−2.502	k = 5, lag = 5	−4.876**	k = 1, lag = 1

Note: Finite sample critical values are obtained from King (2022). * and ** denote 1% and 5% level of significance, respectively.

Table 5
FADL cointegration findings.

Country	Test stat	Min. AIC	Frequency	1 % CV	5 % CV
Germany	−5.819*	−4.776	1.30	−5.304	−4.523
France	−5.223**	−4.502	1.50	−5.335	−4.678
Netherlands	−7.627*	−4.158	2.90	−5.203	−4.525

Note: * and ** denote the rejection of the null of no-cointegration at 1 % and 5 % levels, respectively.

The FADL test statistics are absolutely larger than the CV for all three countries. Thus, there is long-run co-movement between CO_2 emissions, environmental patents, human capital, and GDP. Having established the cointegration, the study first estimates the coefficients using FMOLS and presents them in Table 6.

Table 6
FMOLS with Fourier approximations.

	Coefficient	Std. dev	t-Statistic	Prob.
Germany				
lnGDP	18.587*	0.582	31.917	0.000
$\ln GDP^2$	−0.906*	0.027	−32.780	0.000
lnHC	−0.931*	0.104	−8.929	0.000
lnEPAT	−0.084*	0.011	−7.495	0.000
C	−91.428*	2.994	−30.527	0.000
SSIN	0.051*	0.002	21.350	0.000
CCOS	0.048*	0.002	21.308	0.000
France				
lnGDP	20.859*	3.375	6.180	0.000
$\ln GDP^2$	−0.967*	0.162	−5.939	0.000
lnHC	−5.082*	0.366	−13.849	0.000
lnEPAT	0.032	0.031	1.050	0.300
C	−104.999*	17.452	−6.016	0.000
SSIN	−0.003	0.008	−0.406	0.686
CCOS	−0.019***	0.011	−1.776	0.083
Netherlands				
lnGDP	18.653*	2.425	7.689	0.000
$\ln GDP^2$	−0.869*	0.114	−7.587	0.000
lnHC	−2.985*	0.337	−8.834	0.000
lnEPAT	0.054	0.038	1.440	0.157
C	−94.270*	12.635	−7.460	0.000
SSIN	0.021**	0.008	2.455	0.018
CCOS	0.017**	0.006	2.678	0.010

Note: See the notes for Table 3.

The findings for Germany indicate that the EKC hypothesis is valid. Human capital and environmental patents support CO_2 minimization. A 1 % upsurge in human capital decreases CO_2 emissions by 0.93 %, and a 1 % rise in environmental patents curbs environmental degradation by 0.08 %.

The EKC hypothesis is also valid for both France and the Netherlands. Specifically, human capital plays a key role in reducing CO_2 emissions, but environmental patents do not affect carbon neutrality targets. The Fourier terms are statistically significant in the modeling for the countries, with the exception of sine in France.

Moreover, the DOLS approach is used for the robustness check and the outcomes are presented in Table 7.

As Table 7 presents, the results fully support the results of FMOLS. Therefore, it can be noted that the empirical results are robust and they can be relied upon to argue various policy options. The results of the empirical investigations are shown visually in Fig. 4.

In summary, the EKC hypothesis is valid for all countries examined. Human capital has a supporting effect on ensuring carbon neutrality. Environmental patents are effective only in the German case, whereas they are not beneficial for both France and the Netherlands.

5. Conclusion and policy implications

5.1. Conclusion

Carbon neutrality along with environmental issues have recently become a major concern for countries, societies, and scientists. As the negative impacts of climate change on parties have increased, so have efforts to combat them. For example, most countries have set a goal of becoming carbon neutral by a certain date. To become climate neutral, of course, an economy must achieve various sub-goals. In this context, both policymakers and scientists have considered a variety of factors. This study focuses on technological progress (as measured by environmental patents) while also considering the role of income and human capital in achieving carbon neutrality targets in the leading EU countries (Germany, France, and the Netherlands).

Table 7
DOLS with Fourier approximations for the Robustness.

	Coefficient	Std. dev	t-Statistic	Prob.
Germany				
lnGDP	13.954*	2.479	5.628	0.000
$\ln GDP^2$	−0.685*	0.117	−5.837	0.000
lnHC	−0.639***	0.346	−1.844	0.077
lnEPAT	−0.131*	0.042	−3.102	0.004
C	−67.336*	12.745	−5.283	0.000
SSIN	0.051*	0.010	5.111	0.000
CCOS	0.042*	0.007	5.828	0.000
France				
lnGDP	19.183**	7.905	2.426	0.020
$\ln GDP^2$	−0.901**	0.384	−2.346	0.024
lnHC	−4.025*	0.656	−6.131	0.000
lnEPAT	0.038	0.058	0.664	0.510
C	−95.839**	40.861	−2.345	0.025
SSIN	−0.005	0.017	−0.289	0.774
CCOS	0.004	0.018	0.246	0.806
Netherlands				
lnGDP	43.632*	12.122	3.599	0.002
$\ln GDP^2$	−2.062*	0.573	−3.594	0.002
lnHC	−2.444***	1.305	−1.871	0.082
lnEPAT	0.222	0.206	1.075	0.300
C	−226.310*	63.125	−3.585	0.003
SSIN	−0.005	0.017	−0.299	0.769
CCOS	0.056**	0.024	2.320	0.035

Note: See the notes for Table 3.

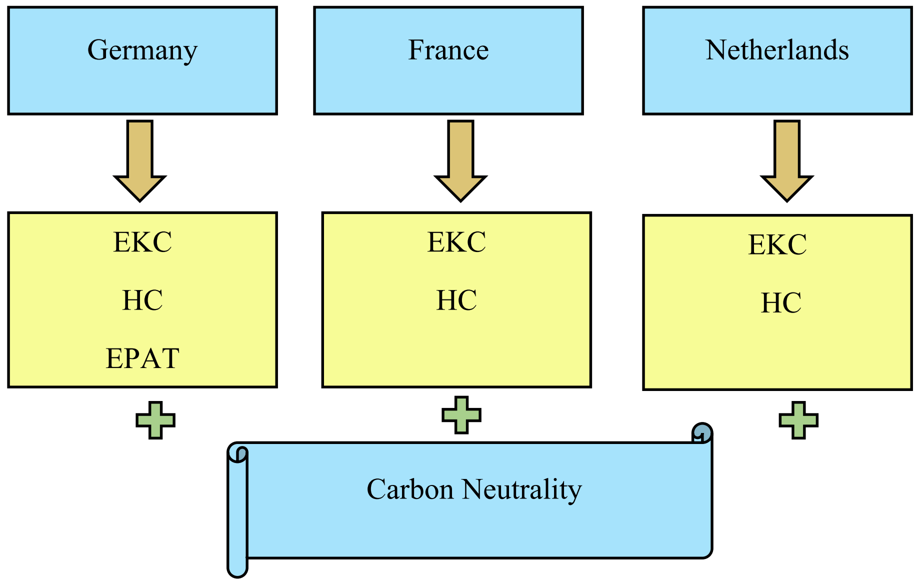

Fig. 4. Visual summary of the findings.

Using the most recent dataset available and conducting Fourier-based approaches, the study finds that environmental patents make a positive contribution to mitigating CO_2 emissions in Germany, while they are not effective in curbing CO_2 emissions in France and the Netherlands. Moreover, human capital dampens CO_2 emissions and the EKC hypothesis is valid for all countries studied, implying that an increase in income level has a curbing effect on CO_2 emissions. The results suggest that France and the Netherlands should invest more in environmental patents so that they can benefit from environmental patents in reducing CO_2 emissions, while Germany has the option of continuing to rely on environmental patents to ensure the country's carbon neutrality goal.

5.2. Policy implications

As the study provides robust empirical results, these can be used to argue various policy options for ensuring carbon neutrality in the countries examined in this study. Thus, assuming that income is the most critical factor in terms of carbon neutrality among all included variables, countries should continuously develop the structure of economic growth. Moreover, the validity of the EKC hypothesis shows that these countries can improve their environmental conditions as per capita income increases. To do so, countries should redirect financial resources from their rising income to eco- friendly technologies and the promotion of clean energy sources. The technique effect of the EKC hypothesis can make a greater contribution to mitigating CO_2 emissions if income is directed to eco-friendly technologies.

In addition to income, human capital development plays a critical role in achieving countries' carbon neutrality goals. Educated people can engage in more environmentally friendly consumption behaviors and are more likely to use clean energy. In addition, increasing human capital increases individuals' income and wealth, and high-income people demand to live in a better environment. Therefore, countries should use human capital as an important policy tool in formulating their environmental policies to ensure carbon neutrality.

Environmental patents play an effective role in CO_2 reduction only in the German case. However, in both France and the Netherlands, they have no impact on CO_2 emissions. Patent developments in these two countries lag behind those in Germany. Environmental patents can have a reducing effect on CO_2 emissions in several ways, such as the diffusion of clean energies in the transportation sector, clean and carbon-free waste management, and the improvement of ecological quality by reducing energy demand through the avoidance of losses in energy distribution and transmission. For these reasons, similar to Germany, it is crucial for France and the Netherlands to make progress on patents in order to benefit from the carbon reducing effects of environmental patents. In this context, it can be suggested that Germany should continue to rely on environmental patents to ensure carbon neutrality, and that both France and the Netherlands should re-structure their initiatives, budgets, and approaches to increase environmental patents. Thus, environmental patents can also be effective in curbing CO_2 emissions in France and the Netherlands.

5.3. Future direction

This study has better content and takes a comprehensive empirical approach. In this context, the study examines three leading EU countries in ensuring carbon neutrality targets from the perspective of technological progress. Nevertheless, the study has some limitations, which new research can consider as future research directions. First, the study only examines three EU countries that are leaders in patents. Therefore, new studies can include more countries. They can even include both leading and lagging countries from the patent perspective to get a better comparative study. Second, the study considers patents, income, and human capital as regressors. Future studies could consider energy-related R&D expenditures for solar and wind energy in addition to patents. Fourth, this study considers environmental patents as a whole, but there are also different types of environmental patents. Future studies can separately analyze the effects of transportation-, waste-, and energy-related environmental patents on carbon neutrality and provide specific suggestions. Fifth, since the study performs Fourier-based approaches and neglects the frequency information of the variables, new studies can use wavelet-based methods. Therefore, time and frequency domains of the data can be considered in new studies. Overall, further studies can enrich the current knowledge by considering the above points when designing new research.

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CRediT authorship contribution statement

Ugur Korkut Pata: Supervision, Methodology, Software, Conceptualization, Writing – original draft, Writing – review & editing. **Mustafa Tevfik Kartal:** Data curation, Writing – review & editing, Investigation. **Shahriyar Mukhtarov:** Investigation, Writing – review & editing, Writing – original draft.

Data availability

Data will be made available on request.

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Ugur Korkut Pata. Assoc. Prof. Dr. Ugur Korkut Pata is an associate professor of economics at the Faculty of Economics and Administrative Sciences, Osmaniye Korkut Ata University, Türkiye. He received his Ph.D. degree in 2019 from Karadeniz Technical University in Türkiye. His research interests include energy economics, macroeconomics, and econometrics. He has published in several journals indexed in the Web of Science Core Collection, such as Ecological Indicators, Energy, Gondwana Research, Journal of Cleaner Production, Resources Policy, and Renewable Energy. The researcher is among the 2 % of the world's most influential scientists for 2021, 2022, and 2023 listed by Stanford University. Dr. Pata also became the youngest associate professor of economics in Türkiye at the age of 29. Pata's Ph.D. thesis titled "An Empirical Analysis of the Environmental Kuznets Curve with Types of Energy Consumption: The case of Türkiye" was awarded the best Ph.D. thesis of 2019 by the Environment Foundation. Dr. Pata also serves as Associate Editor of Web of Science-indexed journals such as Geoscience Frontiers and International Journal of Energy Research.

Mustafa Tevfik Kartal. Assoc. Prof. Dr. Mustafa Tevfik Kartal is a capital market professional. He received a Ph.D. in banking from Marmara University, İstanbul/Türkiye in 2017 and had an Associate Professor degree in banking from Inter-Universities Board, Ankara/Türkiye in 2020. His research interests mainly focus on finance, economics, energy, and environmental areas. He has authored 2 books, 2 book reviews, 22 book chapters, 141 articles, and 12 proceedings in Turkish and English, most of which are indexed in SSCI and SCI-E indices. Also, his 21 articles have been under review. Besides, he has taken a guest editorship role in prestigious journals, in Elsevier and Springer. Moreover, he has been working on various articles in finance, economics, energy, and environmental areas. Furthermore, he has a reviewer role in 110 journals indexed in SSCI and SCI-E indices as well.

Shahriyar Mukhtarov. Assoc. Prof. Dr. Shahriyar Mukhtarov is a professor of the Department of Economics at Vistula University, Poland. Dr. Mukhtarov received his M.A. from Marmara University in 2012 and completed his Ph.D. in Banking at Marmara University in 2016. The holder of several national and international awards, Dr. Mukhtarov has realized various research projects in Macroeconomics and Microeconomics and published numerous scientific articles on Monetary and Fiscal Policy, Sustainable Development, Energy Economics, and Banking in peer-reviewed journals that are indexed by the Web of Science and Scopus databases. He has served on many editorial boards and as a referee of many journals. In addition, Mukhtarov completed research entitled "Exploring Exports-Driven Growth through Free Trade Agreements among CAREC Members: Learning from the Pak-China Free Trade Agreement" under the CAREC Institute CTTN Research Grants Program. He also delivers lectures on Research Methods, Economic Development, Microeconomics, Macroeconomics, and Monetary Policy. Mukhtarov's research interests include energy economics, sustainable development, monetary economics, and building and applying econometric models for policy purposes.