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Research article

The effects of environmental patents on renewable energy consumption

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Abstract: Environmental degradation and energy security are two of policymakers' most crucial concerns, with an increasing emphasis on renewable energy development. Studies regarding the role and influence of environmental technology patents in this context become necessary and can provide the empirical evidence needed for public policy decisions in terms of the benefits they bring compared to other innovation measures. Thus, our aim was to capture the effects of environmental technology patents on renewable energy consumption in OECD Member States over the period 2000–2021. We applied the general dynamic panel model with heterogeneous slopes and interactive fixed effects, controlling for cross – sectional dependence and long-run error – correction models based on (Pesaran, 2015) and implemented by Ditzen (2018), and Blackburne III & Frank (2007), respectively. The empirical results demonstrated that environmental technology patents can be interpreted as effective mediating mechanisms for increasing renewable energy consumption, thus contributing to a reorientation of activities and consumption toward sustainable development. In other words, environmental patents appear in the transformation equation as the main trigger for innovation, generating a growing influence as the demand for the use of renewable energy sources increases, thus facilitating the transition process towards a (cleaner) and affordable energy market. Based on these results, we believe that policymakers and regulators should pay more attention to the research financing related to the investment and patenting of new environmental technologies, promoting a policy of encouraging and enforcing green technologies, regardless of their scope of application.

Keywords: renewable energy consumption; environmental patents; energy efficiency; sustainability

JEL Codes: O34, Q55, Q56

Abbreviations: OECD: Organization for economic cooperation and development; REC: Renewable energy consumption; PET: Patents on environmental technologies; PEC: Primary energy consumption; FDI: Foreign direct investment; URB: Urban population; GHG emissions: Greenhouse gas emissions; R&D expenditures: Research and development expenditures; CO_2: Carbon dioxide; PTS: Panel time series; UNFCCC: United nations framework convention on climate change

1. Introduction

Droughts, forest fires, shrinking of the polar ice cap, thawing permafrost, and increased mortality and morbidity are some of the negative impacts of climate change. A major contributor is the energy industry, which is responsible for a large amount of emissions. The extraction of fossil fuels, processing and distribution of energy from traditional sources not only exacerbate the effects of climate change through associated emissions, but also hinder the transition to a climate neutral economy.

In line with the multilateral climate policy framework set out in the Paris Agreement, many member states of the Organization for Economic Cooperation and Development (OECD) have introduced various measures to address these problems and make progress towards their environmental goals. In this context, the adoption of renewable energy sources is proving to be an indispensable element of these policies. Due to their ability to provide electricity that produces limited, if not zero emissions, renewable energy sources are enjoying increasing attention as a result of society's awareness of the need for a healthy environment (Ang et al., 2022). Moreover, the widespread adoption of renewable energy not only offers a viable solution to combat climate change, but also contributes to energy security. Incorporated into this equation are patents on environmental technologies (PETs), which serve as indicators of technological innovation. Kang & Sohn (2024) argue that patents are at the core of environmental technology innovation activities. A literature review by Makeeva et al. (2024) emphasizes that green patents stimulate research and development in sustainable technologies. In this context, PETs are a viable and effective option to increase energy efficiency and reduce CO_2 emissions. The claim is based on the idea of collaboration between governments, both in the field of environmental innovation and research and development. This can make market integration of environmental technologies more attractive and allow local businesses to take advantage of them. When energy efficiency and penetration of renewable energy sources are strengthened, the foundations for energy sustainability can be created in harmony with environmental sustainability (Elavarasan et al., 2023).

The contributions of the paper are as follows. Regarding the literature, we have not found any study that directly examines the correlation between PETs and renewable energy consumption (RECs) in OECD countries. Although the previous literature addresses to a considerable extent the patenting issues and the need for widespread adoption of renewable energy sources, most of these studies focus on discrete elements without specifically investigating the direct link between PETs and RECs. Thus, we extend the literature and, at the same time, try to emphasize the growing importance of patents on environmental technologies in terms of energy efficiency recovery and environmental sustainability. Despite the dramatic growth in the number of environmental patents and RECs, greenhouse gas (GHG) emissions remain at extremely high levels in OECD countries. This situation underlines the importance of conducting in-depth research to assess to what extent PETs and the uptake of renewable energy sources really contribute to reducing GHG emissions. Thus, we ask the following question: How can we fully understand the impact of eco-innovations on the energy transition without directly exploring the link between PETs and RECs? Furthermore, we note that most studies (Coluccia et al., 2020; B. Wang et al., 2024) use R&D expenditures as a proxy for innovation. However, R&D expenditures are seen rather as an input to the innovation process, than a result of this process, whereas patents are a tangible outcome of the innovation process. Finally, research results are relevant for the design and implementation of policies that encourage green technologies and sustainable development. Thus, our study opens the way for new research directions in the field of the transition to RECs, which can provide the empirical evidence needed to inform public policy decisions aimed at enhancing sustainable development. To fill this gap in the literature, our objective is to analyze the effects of patents of environmental technologies on renewable energy consumption, using a panel dataset from OECD countries for the period 2000-2020. By examining the situation of OECD member countries, characterized by well-established governance structures and environmental regulations, we can assess the effectiveness of these mechanisms in facilitating the energy transition.

Our research is structured as follows: In Section 2, we review environmental challenges and approaches in the literature on the correlation between renewable energy and environmental technology patents to justify the research hypotheses. In Section 3, we present the econometric methods used. In Section 4, we detail the data used in the modeling, and in section 5, we include the major results obtained and related discussions, with research limitations and future implications highlighted.

2. Policies and science on the environmental challenges: Current progress

One of the most pressing challenges we face today is anthropogenic climate change, the negative effects of which are noticeable on the global economy. The World Meteorological Organization (2023) published a report at the end of October 2023, highlighting that the global average temperature was about 1.46°C above the 1850-1900 baseline.

Unless rigorous climate measures are implemented, the global average temperature could reach a critical value, intensifying natural disasters. At the United Nations Climate Change Conference (COP27) in Egypt, the United Nations Secretary-General emphasized that *"the red line we must not cross is the line that takes our planet beyond the 1.5°C temperature limit"* (UNFCCC, 2022). Furthermore, COP27 emphasized that more needs to be done to reduce CO_2 emissions, especially as the war between Russia and Ukraine has made the situation much more complicated.

There were lengthy discussions about limiting the increase in global average temperature and the impact that the conflict between Russia and Ukraine has on the climate environment, but nevertheless, no new measures to reduce CO_2 emissions were adopted at summit that would be adjusted to the events that have taken place during that period. The issue was very well known to the 197 parties, as the UN Conference took place from November 6-18, 2022, and Russia invaded Ukraine on February 24, 2022. The conflict between Russia and Ukraine, which has dragged on for more than 2 years, has had far-reaching effects on the global economy, trade, people's lives, and has also caused an energy and food crisis, just as the world struggles to meet climate goals.

During wars, GHG emissions are notoriously neglected, but they are particularly important. A group of researchers investigated the various actions that contributed to the increase in GHG emissions during the conflict between the two countries, from fuel used by vehicles, to forest fires, to changes in energy consumption in the European Union and the subsequent reconstruction of buildings and infrastructure. Each deflagration of a rocket or projectile has contaminated the air, water, and land with toxic substances (de Klerk et al., 2023). Numerous industrial facilities were hit, causing uncontrolled releases of chemicals. Following the investigation, the researchers concluded that GHG emissions attributed to twelve months of war amounted to about 120 million tCO_2 (de Klerk et al., 2023). The authors note that this amount is equivalent to the total number of emissions generated during the same period in a country such as Belgium, which has an area of 30,688 km^2 with a population of about 11.59 million. The researchers also looked at changes in the European Union's energy mix, where they identified that the EU burned more coal during the war period due to very high gas and oil prices. Furthermore, large amounts of emissions have been produced by airlines rerouting their flights to avoid Russian and Ukrainian airspace. As they say, however, in every crisis there is an opportunity: It is worth noting that while this conflict has caused a great deal of damage to many countries, it has also contributed to some extent to the transition to renewable energy sources, drawing even more attention to the need to reorient energy production and consumption, with its negative consequences. Currently, there is a huge gap between current national climate plans and what is needed to limit the global average temperature increase. Where are we going wrong?

After a year of record heat and drought, a new meeting of world leaders is taking place at the United Nations Climate Change Conference (COP28), hosted by the United Arab Emirates, but G20 member countries have not been able to reach a common agreement, and countries such as Russia have mentioned that they will oppose the phase-out of fossil fuels (Voïta, 2023). There are some initiatives though. The United Arab Emirates has launched a $30 billion fund, ALTÉRRA, to boost positive climate action. Furthermore, the UAE, along with other countries around the world, has proposed that COP28 emphasize technologies to capture and store CO_2 emissions underground. While the International Energy Agency recognizes the crucial importance of these technologies for meeting climate goals, they are expensive and not currently widely used. For example, the European Union is concerned that these technologies will be used to justify the perpetuation of fossil fuels consumption by some countries.

Striking the optimal balance between development and environmental protection is a priority for policymakers (Oyebanji et al., 2022; Si Mohammed et al., 2024), but also considering the large proportion of GHG emissions are generated by our consumption behaviors and habits (Adebayo et al., 2021).

3. Brief literature review on patent analysis

In modern society, innovation is one of the fundamental components of socio-economic development, as it manifests through the introduction of new ideas, technologies, and methods that contribute to improving the quality of everyday life. In the present context, patents are assuming an extremely important role in promoting technological innovation, which is reflected in the international community’s growing commitment to patents to combat climate change. By the end of 2022, more than 32,000 patents had been granted for environmental technologies, according to the National Center for Science and Engineering Statistics (2024).

Ever since Lanjouw & Mody (1996) analyzed environmental patents, a new horizon has opened up for studying the relationship between innovation and sustainability. From that time on, many studies have been devoted to examining the effects of innovations on environmental science. In this section we provide an overview of previous studies on patenting in this area and summarize the main findings of each study. We divide the literature into two parts: The first part highlights the link between innovation and various environment-related indicators, and the second part analyzes the link between renewable energy and the environment.

Nguyen et al. (2020) analyzed the role of information and communication technologies (ICTs) and innovation in increasing CO_2 emissions and economic growth using the OLS model. The empirical results showed that there are statistically significant relationships between CO_2 emissions, ICT and innovation, both in the short-run and the long-run for the 13 selected G-20 countries. In other words, ICT and innovation help reduce CO_2 emissions, creating a healthy environment. Similarly, Ullah et al. (2021) showed that patent applications improve environmental quality in the short run, whereas the effect is insignificant in Pakistan in the long run.

To better understand the effects of innovation on sustainable development, Wang et al. (2023) examine the effects of technological innovations, financial development, renewable and non-renewable energy, and FDI inflows on environmental footprint. According to the empirical results, renewable energy and technological innovation mitigate the level of environmental degradation in the 14 developing economies in the European Union. Also, Onwe et al. (2023) examine the effect of renewable energy, non-renewable energy, globalization, technological innovation, and environmental taxes on the environmental footprint for G-7 economies. The robust method of moments quantile regression has been used in this research and the results show that technological innovation is associated with carbon footprint reduction.

Alofaysan et al. (2024) investigate the effect of green technology, digitalization, renewable energy use, environmental taxes, GDP, energy prices and population on energy efficiency. Using the number of green patents to highlight the effects of innovation, the empirical findings show strong evidence of their positive influence on energy efficiency. Specifically, a 1% increase in patents leads to a 0.0374 unit increase in energy efficiency. Hossain et al. (2024) also show that green technologies boost renewable energy consumption. To demonstrate the link between green patents and environmental sustainability, Tiwari & Mohammed (2024) adopt the CS-ARDL model, which demonstrates that green patents, along with green energy, has a positive impact on environmental sustainability in all quantile.

While some studies indicate that patents help to reduce CO_2 emissions and thus improve the quality of the environment, some studies have found insignificant impact. In this context, Yıldırım et al. (2022) show that innovation, as measured by green patents, has a non-linear impact on CO_2 emissions in the energy sector in OECD countries. Alataş (2022) empirically examines the link between CO_2 emissions and environmental technologies for the transportation sector. The findings indicate that environmental technologies have a statistically insignificant positive effect on CO_2 emissions in the transportation sector. In other words, environmental technologies contribute to CO_2 emissions.

The second part examines the link between renewable energy and the environment. Several empirical studies and analyses by international organizations have shown that renewable resources are the most important tools to achieve climate goals.

Empirical results reveal that adoption of renewable energy sources leads to environmental performance. For example, Zakari et al. (2023) demonstrate that renewable resources improve environmental performance in China and Japan. This validates the theory that green technologies bring environmental benefits. Using panel cointegration analysis, Bakry et al. (2023) also argues that renewables significantly reduce CO_2 emissions. Similar results have also been obtained by Mohammed et al. (2024), Fakher et al. (2023), Alnour et al. (2024), Rej et al. (2024). However, as with many indicators, there are also studies indicating that renewable energy has no significant effect in reducing pollution (Adams & Nsiah, 2019). It is possible that these conflicting results are due to the differentiated methodologies that were applied and the specific particularities of each sample under analysis.

Researchers have focused on how technological innovations can address environmental pollution problems at the expense of their potential to promote sustainable development. With this in mind, we aim to fill this gap by providing a distinct investigation of the correlation between patents on environmental technologies and renewable energy consumption in OECD countries. Therefore, from an empirical point of view, the study makes a valuable contribution to the literature. First, we have not found any researchers that analyze the correlation between PETs and RECs in OECD countries. Although researchers address to a considerable extent the issues of patents and the need for widespread adoption of renewable energy sources, most focus on discrete elements without specifically investigating the direct relationship between PETs and RECs.

Second, we focus on the impact of patents and not on other indicators such as R&D expenditures. R&D expenditures, used as a proxy for innovation, are seen rather as an input (R&D funding) into the innovation process and not as a result of the innovation process, whereas PETs are a tangible outcome of the innovation process. Even more, PETs are specific to those technologies that have a positive impact on the environment, and this makes them a direct indicator of progress in green innovation. Seen from this perspective, R&D can be distributed across several domains, not necessarily related to sustainability. The importance of understanding the impact of patents on environmental technologies on renewable energy consumption across a broad spectrum is fundamental for the development of energy and environmental policies.

4. Materials and methods

4.1. Methodology and data

In the context of intensifying environmental degradation and global warming, effective implementation of environmental regulations and the adoption of green technologies remain key catalysts for mitigating these challenges.

As an attempt to minimize the negative effects of global warming, and thus climate change, policymakers and researchers have identified green technologies as a fundamental strategy for achieving the 17 Sustainable Development Goals (Oyebanji et al., 2022). Accordingly, the current research aims to examine the impact of environmental technology patents on renewable energy consumption in Organization for Economic Co-operation and Development member states.

The data used is a panel data type (with unit being representing by an OECD country and time being quantified yearly). Such data types (that are also time series, being of importance when time length is large enough) are usually named in the econometric literature as Panel Time Series (PTS), see Ditzen (2022). In panel data series, the difference between units (in our study Country effects) or time (named time effects) should be controlled. PTS models often contain common factors (interactive fixed effects) and dependence across cross-sectional units that also should be addressed.

The first major problem to be addressed is the presence of non-stationarity in data when using an ordinary least squares model (O.L.S.), which can lead to spurious regression. The data must be tested for stationarity, and the most common way for testing the existence of non-stationarity is (in a general model), being equivalent to checking for the existence of a unit root, based on the AR(1) model, presented in equation no. 1.

In the following equation, it is to be tested $\rho_i = 1$, the unit root being present if the value is equal to one. To test the stationarity in panels (equation no. 1), we have employed a variety of tests (for unit roots) in the panel dataset. Some tests Levin et al. (2002), Harris & Tzavalis (1999), Breitung & Das (2005), Im et al. (2003) and Fisher-type (Choi, 2001) have the null hypothesis H_0: *All the panels contain a unit root*. The Hadri Lagrange multiplier (LM) test (Hadri, 2000) has the null hypothesis H_0: *All the panels are (trend) stationary*. The unit root tests in panel data are based on equation 1:

$$y_{it} = \rho_i y_{i,t-1} + z'_{it}\gamma_i + \epsilon_{it} \tag{1}$$

For time series, as in our case - panel data (that account for individual means) the variables are cointegrated (cointegration tests are available on demand), so an error-correction model (E.C.M.) is needed. In this case, even if the data is nonstationary in level (the error-term could also not be stationary), the first-difference can be applied, resulting in an error-correction model with stationary residuals.

In the next equation equation (2) the methodology for auto-regressive distributed lag models with p and q lags A.R.D.L. (p,q), as a theoretical base for the E.C.M. model (3). Regarding the auto-regressive distributive lag model, T must be large enough, such that the model can be fitted for each group separately. Time trends and other fixed regressors may be included (λ_{it}). If the variables in (2) are, for example, I(1) and co-integrated, then the error term is an I(0) process for all *i* (see Blackburne III & Frank (2007)). A principal feature of co-integrated variables is that the responsiveness to any deviation from long-run equilibrium can be estimated. This feature implies also an error correction model in which the short-run dynamics of the variables (in the system) may be influenced by their deviation from equilibrium. Thus, it is common to re-parameterize (2) into the error correction equation (3) (we have kept the notation from Blackburne III & Frank (2007)).

$$y_{it} = \ y_{it} = \sum_{j=1}^{p} \lambda_{ij} y_{i,t-j} + \sum_{j=0}^{q} \delta'_{ij} X_{i,t-j} + \mu_i + \epsilon_{it} \tag{2}$$

In the case of non-stationary variables, and cointegration, an error-correction term is used, so the model became as equation no. 3.

$$\Delta y_{it} = \phi_i\left(y_{i,t-1} - \theta'_i X_{it}\right) + \sum_{j=1}^{p-1} \lambda^*_{ij} n \Delta y_{i,t-1} + \sum_{j=0}^{q-1} \delta'^*_{ij} \Delta X_{i,t-j} + \mu_i + \epsilon_{it} \tag{3}$$

where:

i = 1, 2, . . ., N are the number of groups; t = 1, 2, . . ., T are the number of periods; X is a k × 1 vector of explanatory variables;

δ = it are k × 1 coefficient vectors;

(p, q_1 $_{...,}$ q_k) are A.R.D.L. lags;

ij are scalars; and

i is the group-specific effect.

Long-run relationships describe how one or more variables react to changes in the steady state - the relationships between macroeconomic variables such as GDP, inflation, the effects of investments, exchange rates, education, or technological progress on economic growth. We consider that renewable energy and tax levels are cointegrated and perform in the same way as the variables nominated above.

The choice for the long-run effects methodology is related to the following important facts:

- some variables are not-stationary in levels, so "classical" panel data models (fixed and random effects) could be biased (for the comparison the results are presented in the *Appendix*);
- the non-stationary variables are possibly co-integrated, but with cross-sectional factors (the tests for stationarity and factors presence are presented in the section *Empirical Results*);

- economic variables, such as *Gross Domestic Product*, *Gross Domestic Product per capita GDPcap*, or technological, as in our case *Renewable energy* are usually a lagged dependent variable, so lagged models should be applied.

The presented methodology by far does not account for the presence of the common factors and cross-sectional, but PTS models often contain such ones and dependence across cross-sectional units. In the presence of common factors, they can influence all or many cross-sectional units at the same time.

To determine the presence of cross-sectional factors, we use the methodology proposed by Bai & Ng (2002), Onatski (2010), Ahn & Horenstein (2013), and Gagliardini et al. (2019) and implemented by Ditzen and Reese (2023). Strong cross-sectional dependence occurs if common factors are part of the observed variables (see Ditzen (2022)). Considering the general dynamic panel model with heterogeneous slopes and interactive fixed effects (as in 4), the common factors in $f_{1,t}$, and $f_{2,t}$ can be written as in 5, and 6, having the coefficients (factor loadings) $\gamma_{x,1,I}$, and $\gamma_{x,2,i}$. The full equations are rewritten in 7. Cross-section dependence occurs if the factor loadings are not equal to zero, and the first order problems for the estimator arise if $\gamma_{x,1,i}$, and $\gamma_{x,2,i}$ are also not equal to zero.

$$y_{i,t} = \lambda_i y_{i,t-1} + \beta_i x_{i,t} + u_{i,t} \tag{4}$$

$$x_{i,t} = \gamma_{x,1,i} f_{1,t} + \gamma_{x,2,i} f_{2,t} + \xi_{i,t} \tag{5}$$

$$u_{i,t} = \gamma_{u,1,i} f_{1,t} + \gamma_{u,3,i} f_{3,t} + \epsilon_{i,t} \tag{6}$$

$$y_{i,t} = \lambda_i y_{i,t-1} + \beta_i \left(\gamma_{x,1,i} f_{1,t} + \gamma_{x,2,i} f_{2,t} + \xi_{i,t}\right) + \gamma_{u,1,i} f_{1,t} + \gamma_{u,3,i} f_{3,t} + \epsilon_{i,t} \tag{7}$$

Papers such as Pesaran (2015) propose a test for weak cross-section dependence, the CD-test (as in 8) tests the null hypothesis *H0: weak dependence* vs. alternative *H1: strong dependence*.

$$\mathrm{CD} = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij}\right) \tag{8}$$

Further developments are made by Fan et al. (2015), Pesaran (2021), Xie & Pesaran (2022), and Juodis & Reese (2022).

The empirical results are presented and explained in the next section.

4.2. Data description

Our research examines the impact of environmental technology patents on renewable energy consumption in OECD member countries over the period 2000–2020. Due to data availability, 36 OECD member countries were included in this analysis, excluding the ones where the time series was not complete. The selection of this timeframe was based on data availability and reliability to ensure a comprehensive analysis. The data is panel type, strongly balanced, and with no gaps. To control the outliers, the data is trimmed to 99%.

The dependent variable in the empirical analyses is renewable energy consumption (REC). The idea of achieving climate neutrality by 2050 has now become a global consensus and seems to be an unstoppable trend, due to the public awareness of the negative impact that carbon dioxide emissions can have on future generations. In this sense, the key component in achieving climate neutrality is renewable energy sources. Compared to coal-fired power plants, renewable energy not only offers a cleaner alternative but also proves to be more cost-effective than traditional fossil fuels (Yuan et al., 2022). By integrating this variable into our analyses, we aim to improve our understanding of the dynamics and key factors influencing the transition to sustainable energy. The explanatory variable of our study is represented by patents for environmental technology (PET) as a proxy for green technologies. Technological innovation can be measured by several indicators (e.g. number of scientific staff, R&D expenditure, gross domestic expenditure on R&D), but these are seen more as inputs (Johnstone et al., 2010). Consequently, patents emerged as an outcome measure. Over the past decades, numerous initiatives have been established to promote ecosystem-friendly sustainable growth. In this context, environmental technologies have become increasingly important for improving the use of energy resources and developing green ecosystems (Liao et al., 2014). Integrating this variable into our analysis is important because patents on environmental technologies symbolize a nation's commitment to improving environmental quality and thus contributing to achieving climate goals. In addition, it is well known that increased innovation enables the development of revolutionary technologies capable of ensuring better environmental sustainability. Furthermore, we also include a set of control variables to highlight the impact of other determinants on renewable energy consumption. For example, we chose to integrate FDI into the analysis, as it could accelerate technological progress in host countries. Lee (2013) also argues that FDI can create positive externalities through the deployment of foreign technology and know-how. Therefore, FDI plays a key role in investigating our objective as it can stimulate the development of a modern energy infrastructure and stimulate the creation of new jobs. Given the statistics on urbanization rates in recent years, we also included this variable in the econometric models to determine whether urbanization contributes favorably to the increase in renewable energy consumption. The data we used to quantify the relationship between environmental technology patents and renewable energy consumption were largely extracted from the Sustainable Development Indicators dataset in the World Bank database and the OECD database. A description of the variables included in the panel data analysis, as well as the source of the data, is shown in Table 1.

Table 1. Data description.

Variables	Variable description	Data source	Expected effect (sign)
REC	Renewable energy consumption (% of total final energy consumption)	World Bank	
PET	Patents on environment technologies (% in total)	OECD	+
PEC	Primary Energy Consumption per capita (measured in kilowatt-hours per person per year)	Energy Information Administration	-
FDI	Foreign direct investment, net inflows (% of GDP)	World Bank	-
URB	Urban population (% of total population)	World Bank	+

Table 2. Descriptive statistics.

Variables	Obs.	Mean	Str. Dev.	Min	Max
REC	777	20.4546	15.8789	0.8500	82.7900
PET	723	10.7644	4.1189	0.9200	33.5300
LOGPEC	792	10.6042	0.5927	8.9663	12.1458
FDI	814	4.6647	9.7016	−40.0866	109.0253
URB	792	76.1588	11.1559	50.7540	98.1170
Year				2000	2021
Country				1	37

Table 2 shows the descriptive statistics for the dataset analysed.

To have a complete frame on technologies and practices that improve energy efficiency in OECD countries, statistical analysis was used for our variables, which provides valuable information on the trends and dynamics of different energy and economic indicators. From the attached table, we observe variations in all variables. In the case of the dependent variable (REC), it varies between a minimum equal to 0.8500% of total final energy consumption (United Kingdom, 2021) and a maximum equal to 82.7900% of total final energy consumption (Iceland, 2020. The average renewable energy consumption of 20.4546 over the period analyzed (2000-2020) indicates an increasing emphasis on clean energy sources. The explanatory variable (PET) ranges from a minimum value of 0.9200 (Estonia, 2001) to a maximum value of 33.5300 (Costa Rica, 2002), with an average of 10.7644 over the analysis period. According to the literature, patents are correlated with research and development expenditure. In this context, the more research and development investment there is the possibility of increasing the number of innovative technologies (Baron et al., 2018). The choice of variable is a base for future policy implications: the need for the use of innovations financing stimulants, as a preoccupation of the policy makers. A more comprehensive picture of the evolution of the number of patents on environmental technologies can be analyzed in the Annexes (see Supplementary Fig. A.1).

5. Empirical results

Panel Time Series type (PTS) models often contain common factors (interactive fixed effects) and dependence across cross-sectional units. The initial sets of our data testing refer to the presence of unit-root. The results for Im-Pesaran-Shin and Fisher-type are presented in the following (Table 3). The null hypothesis for Im-Pesaran-Shin and Fisher based on Phillips-Perron tests is *Ho: All panels contain unit roots*, with the alternative *Ha: At least one panel is stationary*.

Table 3. Unit root tests.

Variables	R(zttildebar)	R(p)	R(l)	R(z)	R(pm)	Type
REC	−1.8091**	72.5108	−1.2493	−1.2609	0.0426	I(1)
D.REC	−10.4206***	514.7586***	−22.9578***	−16.0490***	36.8965***	
LOGPEC	2.4991	45.4332	3.2937	3.4280	−2.2139	I(1)
D.LOGPEC	−15.3819***	993.6302***	−45.7700***	−27.4970***	76.8025***	
PET	−6.4946***	238.7873***	−10.0655***	−8.3913***	13.8989***	I(0)
D.PET	−14.9482***	1061.8070***	−48.8850***	−27.4970***	82.4839***	
FDI	−10.6463***	537.3793***	−24.4889***	−16.3586***	38.7816***	I(0)
D.FDI	−16.7887***	1452.2334***	−66.9008***	−33.7477***	115.0194***	
URB	6.2514	561.5094***	−24.9051***	−9.4018***	40.7924***	I(0)
D.URB	1.1570	358.2711***	−11.8981***	−4.3716***	23.8559***	

The results of unit-root tests suggest that the dependent variable *REC* is not stationary in levels, but is stationary in first-difference, being of type I(1). The results obtained for the independent variable *LOGPEC* show that is also I(1), with other independent variables being stationary in levels - I(0). None of the variables are non-stationary in first-difference, so there are no problems related to I(2) type of stationarity. The presence of I(1) type variables imposes the use of error-correction models (EC) to control the non-stationarity process, so the chosen methodology is correct. Another test refers to the variance inflation factor, a test to check if multicollinearity might exist. In the presence of multicollinearity, the relationship between each independent variable and the dependent variable cannot be independently estimated. The VIF tests indicates that there are no multicollinearity problems, and for all the models, the VIFs means being under 5 (the results for the first O.L.S. model are available in *Appendix*, Table A.1).

The first attempt to control country differences is fixed and random effects models. The models analyze the short-run relationships. To control stationarity, the first-difference should be used. The results are available in the *Appendix*, suggesting a positive relationship between patents on environmental technologies and renewable energy (see tables A.2, and A.3), all the coefficients being positive and statistically significant at least at the 10% level.

As data appears to be I(1), we used error-correction models to control for the non-stationarity in residuals. Further, the identification of cross-sectional factors suggests cross-sectional dependence model is implied. The number of cross-sectional factors for the dependent variable is presented in the Appendix table - Table A.4.The identified cross-sectional factors are around 2 (ER -1, GR -1, ED -2) for the dependent variable *REC*, and around 3 factors for the *PET* - (ER -1, GR -1, ED - 3), so the choice for cross-sectional method is correct. The tests identify between 1 to 3 factors for other variables (the results are available on demand). We have ignored estimates from GOL, the criteria from Bai & Ng (2002) often over-selects. The presence of these factors is a premise for using the suggested methodology.

A first naïve attempt to model our relationship between the implied variables (PET and REC) was using the fixed and random effects models (as previously presented), to control only for the heterogeneity between panels. The results (in *Appendix*) agree with the findings of the more complex ECM models, which also control for non-stationarity and cross-sectional factors, and are further presented. The long-run and short-run results (ML - maximum likelihood models (Blackburne III & Frank, 2007)), and cross-sectional O.L.S. Ditzen (2018) for the first interest variable, are available in Table 4. The first two columns, named MG-ML and PMG-ML, present the coefficients obtained using maximum-likelihood for the mean (MG) and pooled mean (PMG) group, error-correction model (E.C.M.) in line with Blackburne III & Frank (2007). The next three columns contain the coefficients of E.C.M. using estimators calculated by the methodology proposed by Pesaran & Smith (1995) and implemented by Ditzen (2018). The coefficients are obtained using the ordinary least squared method (O.L.S.). The control for the cross-section dependence is marked by *c* letter in the column name.

Our results suggest that, in the long run, primary energy consumption *(PEC)* per capita is statistically significant at 1%, registering a negative value, and indicating an inverse relationship between the two variables. Thus, increasing primary energy consumption by one unit leads to a decrease of 0.9612 units of renewable energy sources in the first econometric model. Primary energy consumption is mainly based on non-renewable energy sources (oil, natural gas, coal, nuclear energy) and to a lesser extent on renewables (Liu, 2020). Since early times, fossil fuels have predominated globally, and through this primary energy consumption, there have been considerable increases in the use of non-renewable resources. Moreover, it should not be forgotten that most industries in OECD countries rely on fossil fuels, thus exerting a strong influence on energy consumption. Thus, the results we have obtained agree with economic realities, our expectations and previous literature findings.

Economists think that energy consumption is linked to economic activities and plays a key role in economic development (Liu, 2020). As a result, many researchers have focused on examining the relationship between primary energy consumption and economic growth, as measured by GDP. Most studies have shown that primary energy consumption affects gross domestic product (Aslan et al., 2014; Chiou-Wei et al., 2008; Estevão & Lopes, 2024; Mahalingam & Orman, 2018). We must bear in mind that the relationship between the two variables can be countered by implementing a set of government policies and a change in society's perspective on the importance of sustainable development and the use of renewable sources.

Patents on environmental technologies *(PET)* show a positive and significant result, indicating that their increase corresponds to an increase in the use of renewable energy sources. Our results show that, in the long run, the increase with one unit in PET conducts to an increase between 0.05 and 0.3, varying by the methodologies implied (the calculated coefficients are: 0.0548, 0.1724, 0.0569, 0.3060, 0.1780). There is a clear positive relationship on a long-run between patents and implementation of renewable energy. The results are not surprising, given that renewable energy and air pollution control are the most dynamic clusters of environmental technology patents (OECD, 2009). From mitigating climate change to improving resource efficiency in general, green technologies play a key role in ensuring a sustainable future.

The correlation between environmental technology patents and renewable energy consumption is evident when examined from different points of view. First, environmental technology patents encourage the design and implementation of environmentally friendly solutions, which contribute to the increased uptake of renewable energy. Second, they stimulate the advancement of the circular economy using various innovative waste recycling technologies. By accelerating the patenting of environmental technologies (Kirikkaleli et al., 2023) in OECD countries, important steps can be taken towards achieving the Sustainable Development Goals. Thus, innovation will be at the forefront of this transition (Gielen et al., 2019).

Table 4. Mean Group (MG) and Pooled Mean Group (PMG) maximum likelihood (ML) and O.L.S. Regressions.

Variables	MG-ML	PMG-ML	MG-CS-OLS	PMG-NCS-OLS	PMG-CS-OLS
PEC	−0.9612***	−0.4585***	−0.9374***	−0.2900	−0.6902***
	(0.1056)	(0.0622)	(0.0983)	(0.4232)	(0.2104)
PET	0.0548*	0.1724***	0.0569*	0.3060**	0.1780**
	(0.0860)	(0.0407)	(0.0810)	(0.2116)	(0.1296)
D.PET	−0.0211	−0.1580**	0.0307	−0.1491***	0.0134
	(0.0682)	(0.0631)	(0.0457)	(0.0478)	(0.0295)
D.LOGPEC	−9.9402***	−10.5308***	1.4874	−11.9674***	−0.6402
	(2.6387)	(2.3123)	(2.4081)	(2.2339)	(1.8122)
D.FDI	−0.0021	0.0231	0.0171	0.0114	0.0149
	(0.0430)	(0.0422)	(0.0488)	(0.0432)	(0.0174)
D.URB	11.3573	−12.7316	−16.5137	−4.3650	−0.9538
	(15.9982)	(17.1679)	(35.4502)	(2.9076)	(8.6167)
PET	0.0548*	0.1724***	0.0569*	0.3060**	0.1780**
	(0.0860)	(0.0407)	(0.0810)	(0.2116)	(0.1296)
LOGPEC	4.3528	−8.6629***	−2.2937	−4.2759	−5.7404
	(10.6139)	(1.6914)	(4.7858)	(17.0240)	(3.6257)
FDI	0.0243	−0.0206**	−0.1025	−0.0144	−0.0178
	(0.1432)	(0.0081)	(0.2779)	(0.0645)	(0.0419)
URB	4.7002***	0.1374	1.3835	0.1494	0.2595*
	(1.5460)	(0.0926)	(4.4662)	(1.9848)	(1.6485)
Obs.	756	756	756	756	756
R-sq.			0.1698	0.6306	0.6546
No. of groups	36	36	36	36	36

*Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.*

In the face of the negative effects generated by climate change, governments have established numerous initiatives and implemented multiple instruments aimed at bringing positive changes in society. While some of these policies have proven to be successful, most have not always provided the desired results. To ensure that the policies implemented produce the desired results, the government needs to step up investment in scientific research, including the establishment of research and development centers. By providing adequate financial support, inventors are motivated to create various green technologies (manufacturing solar cells and polysilicon with low-cost physical methods (Zhao et al., 2016)). Furthermore, governments must be prepared to adjust public policies based on new scientific findings. In addition, it is essential to stress the importance of global cooperation. Climate change is a global problem requiring international solutions. Thus, governments should proactively engage in global efforts (e.g., the Paris Agreement) and work together to develop effective renewable energy technologies and strategies.

This result is consistent with the findings of Alola et al. (2024), Azam et al. (2022), Bekun, (2024), Chen & Tanchangya, (2022), Hongqiao et al. (2022), Kirikkaleli et al. (2023), and Oyebanji et al. (2022), among other, but contrast to Li et al. (2022) and Ganda (2019). The results may be influenced by various factors, for example, how patents on environmental technologies are enforced and regulated varies substantially across countries. In addition to this, we must consider that developed countries have the necessary resources and the capacity to adopt various environmental technologies while developing countries face financial, technical, and infrastructural challenges in adopting new technologies. In this case, there is a possibility that developing countries will move more towards adopting polluting technologies. For example, a UNCTAD (2023b) press release points out that there is a huge gap between countries in terms of innovative technologies, with disadvantages for developing countries. In this context, we believe that technology transfer, knowledge sharing, and, most importantly, international cooperation are the major factors that would help developing countries pursue their journey towards sustainable development. Policymakers also need to place more emphasis on certain key areas, including investment in research and development, the promotion of public-private partnerships, and coherent policy frameworks.

OECD countries include many developed and developing countries that are experiencing a faster pace of urbanization, which positively influences renewable energy consumption in the area. This is justified by the fact that the transition of people from rural to urban areas has led to the replacement of traditional fuels (e.g., traditional wood heating) by centralized energy sources. However, in addition to these positive aspects that urbanization generates, we must also consider the production activities that can be stepped up to meet population demand. This could lead to increased CO_2 emissions into the atmosphere. Similar results have been obtained by Mahalik et al. (2021), Poumanyvong & Kaneko (2010), and Zhao & Zhang (2018).

6. Conclusions

The threats to the environment are mainly a by-product of economic progress, which is realized through consumption of energy from non-renewable sources, so rigorous and well-informed government policies are needed to mitigate negative impacts and adjust to new climate realities. In this approach, our study uses panel data for 37 OECD member countries, with a timespan from 2000 to 2021, for evaluating the relationship between environmental patents and renewable energy. To validate our methodology usage, tests for multicollinearity, unit roots stationarity, and cointegration were performed, suggesting that the data are stationary in the first difference and that there is cointegration between the variables involved. Patents on environmental technologies were used as a proxy to highlight the degree of innovation. The results provide important empirical evidence on the relationship between patents on environmental technology and renewable energy consumption in OECD countries, with considerable implications for global policy. We present evidence that, in the long term, environmental technology patents positively influence renewable consumption, suggesting both the need for strengthening national public policies to stimulate the production of environmental patents/transfer of patents to practice, and for closer interstate cooperation for technology transfer between nations, with the goal (strengthening the green economy) being considered a global one. These findings demonstrate that patents on environmental technologies contribute significantly to improving the quality of the environment, serving as catalysts for the technological innovation needed to address contemporary environmental challenges. Our results are in line with other studies in the literature (Alofaysan et al., 2024; Hossain et al., 2024; Yıldırım et al., 2022) that support the idea that technological innovations are essential for achieving climate goals.

Based on the empirical findings, this study recommends that governments of OECD nations should intensify the efforts to promote and mainstream technological innovations by implementing more rigorous public policies tailored to the unique environmental and economic contexts of each nation and region, increasing fiscal incentives and strengthening R&D investments to encourage patent development. Beyond the obvious environmental benefits, such as reducing CO_2 emissions and increasing energy efficiency, these measures also make a significant contribution to the creation of green jobs, which are essential for a sustainable economic sector.

Second, in the context of the intensifying climate crisis, international cooperation at all levels is becoming a key element in promoting technological innovation. Climate change problems cannot be solved by one nation alone. In this context, international cooperation enables nations to work together to develop effective solutions to address contemporary challenges. Furthermore, OECD countries should support and facilitate public-private partnerships to develop green solutions.

At a global level, it is important that governments adopt and implement effective innovation policies that act as drivers of economic progress. These policies should be effective both on their own and in combination with other government efforts (e.g., economic, environmental, infrastructure and fiscal policies), creating a strong framework to foster innovation and sustainability in response to global challenges and socio-economic change. These policies will require cooperation between innovators, the government, the academia, and the society. The results are, therefore, useful for investors and policymakers who want to stimulate the energy sector through public policies.

The paper is also useful because it empirically argues for international cooperation in this field: Since climate change goes beyond national borders, the appropriate treatment can be only at the interstate level. There is a huge gap in the efforts made by the world's countries to develop innovative technologies that contribute to environmental protection (Barra et al., 2019). Therefore, a unified approach across OECD countries (and beyond) to the proposed direction is imperative.

Our study represents original research on the impact of environmental technology patents on renewable energy consumption in OECD member states, consequently paving the way for other specialized studies toward clarifying the role of environmental patents in the transition to a green economy and sustainable development. However, the results obtained are limited by the range of existing data, and it would be desirable both to extend the study to the whole OECD panel dataset and to replicate it for all countries (not only OECD members). It is also recommended that future research on this topic should include more macroeconomic variables, thus providing an even better picture of the influence of environmental patents on renewable energy consumption.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions

Conceptualization, M.O., B.N.F., F.O. and C.D.C.; methodology, M.O., B.N.F., F.O. and C.D.C.; software, M.O., B.N.F., F.O. and C.D.C.; formal analysis, M.O., B.N.F., F.O. and C.D.C.; investigation, M.O., B.N.F., F.O. and C.D.C.; writing - original 643 draft preparation, M.O., B.N.F., F.O. and C.D.C.; writing - review and editing, M.O., B.N.F., F.O. and C.D.C. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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