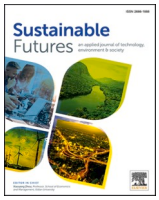
Sustainable Futures 8 (2024) 100352

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures



Assessing the eco-effectiveness of energy R&D technologies and environmental patents: A comparison between Portugal and Spain☆

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ARTICLE INFO

Keywords:
Carbon emissions
Energy R&D expenditures
Environmental patents
EKC
LCC

ABSTRACT

The validity of environmental hypotheses is important for the implications of a sustainable future. In this context, this study investigates the validity of the Environmental Kuznets Curve (EKC) and the load capacity curve (LCC) for Portugal and Spain. Employing the Fourier-ADL approach from 1983 to 2020, the study concludes that the EKC and LCC hypotheses are valid for both countries, that environmental patents improve ecological quality, but that energy-related R&D expenditures have no significant impact. The findings underline the need to support environmental patents with income growth to ensure a sustainable future.

1. Introduction

Environmental problems are an ongoing issue on the political agenda, and countries are working hard to improve their environmental quality. With the Paris Conference and various international agreements, political decision- makers have committed themselves above all to combating climate change. In this context, the determinants of GHG and carbon (CO_2) emissions continue to be frequently studied (see e.g., [6,33,38]).

Various researchers have analyzed CO_2 under the EKC hypothesis. This hypothesis shows that there is an inverted U-shaped interaction between CO_2 and GDP per capita. In other words, the EKC hypothesis shows that societies initially make environmental sacrifices to support economic expansion, but after their income levels and prosperity reach a certain level, they begin to make efforts to improve their ecosystems and increase their ecological quality. Inspired by EKC, Dogan and Pata [13] described the relationship between LCF and GDP as LCC. The LCC is shown in Fig. 1 and is similar in form to the inverse EKC.

The fact that the LCC is in reverse EKC form is related to the fact that the dependent variable is an indicator of ecological quality. The LCC shows that ecological quality initially decreases as income rises. When the prosperity level of society rises to the highest level, the increase in GDP per capita supports the upsurge in LCF proposed by Siche et al. [57]. In this context, the LCC logically provides an assessment of ecology in line with the EKC, but since the LCC incorporates both supply-side (biocapacity) and demand-side (EF) elements of the environment, it provides a more robust assessment option than the EKC in terms of ecological economics.

Based on the turning points of the LCC and EKC hypotheses, the increase in ecological quality is made possible by the technique effect. The technique effect implies that countries can improve environmental quality by allocating more financial resources to environmental technologies as their income increases. In addition, the Porter hypothesis states that polluting firms can promote clean technological advances by exploiting strict environmental regulations, thus contributing to efficiency in production and ecological development through the innovation effect [51]. Technique and innovation effects show that clean technologies that advance with increasing environmental awareness

Abbreviations: ARDL, Autoregressive distributed lag model; EF, Ecological footprint; EKC, Environmental Kuznets curve; EPAT, Environmental patents; ER&D, Energy related R&D technologies; EU, European Union; FADL, Fourier ADL; GFN, Global Footprint Network; GDP, Gross domestic product; GHG, Greenhouse gas emissions; LCC, Load capacity curve; LCF, Load capacity factor; PAT, Patents; R&D, Research & Development; USA, United States of America.

☆ Ethical approval: This article does not contain any studies with human participants performed by any of the authors.Consent for publication: Not applicable. Consent to publish: Not applicable.Availability of data and materials: The datasets analyzed during the current study are available from the corresponding author on reasonable request.

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https://doi.org/10.1016/j.sftr.2024.100352
Received 21 July 2024; Received in revised form 1 October 2024; Accepted 15 October 2024
Available online 17 October 2024

contribute to ecosystem development and that technological progress is a necessary prerequisite for economic and environmental development. Technological progress is therefore an important component of the LCC hypothesis.

The validity of the LCC has already been analyzed for several countries, but no study has yet been conducted for Spain and Portugal. Spain and Portugal are two neighboring European Union (EU) countries that have been comparatively analyzed in the context of the EKC. Moutinho et al. [42] compared the validity of the EKC in Portugal and Spain and found that there is an inverted N-shaped relationship between CO_2 and economic progress in both countries. Moutinho et al. [41] conducted a sectoral analysis in Portugal and Spain and found that the EKC is only valid in one out of five sectors for Spain and six sectors for Portugal in relation to CO_2 in an inverted U-shape.

EU countries are working together to improve ecological quality, but although Spain and Portugal have seen some reduction in CO_2 emissions, there has been no progress in increasing the LCF. Fig. 2 shows the evolution of CO_2 emissions in Spain and Portugal during the analysis period.

Fig. 2 shows that per capita CO_2 emissions in Spain and Portugal peaked in 2005 and are on a downward trend until 2020. However, the CO_2 levels in 2020 are not much lower than the levels in the 1980s. Therefore, it seems that Portugal and Spain should continue their efforts to reduce CO_2. The situation in relation to the LCF and the sustainability threshold is shown in Fig. 3.

Fig. 3 shows that the environmental situation in Portugal and Spain has not been sustainable over the last 40 years. In 2020, the LCF value in Portugal is 0.39 and in Spain 0.44. This situation indicates that the two countries are consuming more than twice as many natural resources as the current ecological resources. For this reason, the governments of Spain and Portugal should also develop solutions to increase the LCF. Can technological progress help to reduce CO_2 emissions and increase the LCF in Spain and Portugal? Are the LCC and EKC hypotheses valid for Portugal and Spain? This study aims to answer these research questions using the FADL approach.

The adaptation of technologies is important for ecological cleanliness and sustainable economic progress [35]. Advances in energy technologies are expected to support the green transition [60]. Countries have turned their focus to investing in green technologies and R&D expenditures to combat climate change [25]. Eco-friendly technologies can help tackle global warming by reducing CO_2 emissions into the environment and minimizing drainage to fossil fuels [11]. In this context, the paper investigates the environmental impact of EPAT and ER&D for Portugal and Spain. Fig. 4 shows the evolution of environmental patents over time for two countries.

Fig. 4 shows that Portugal has made considerable progress in EPAT since 2014 and Spain since 1995. Both countries have seen a decline in environmental patent applications between 2018 and 2019, due to the coronavirus-19. Spain's EPAT figures are much higher than Portugal's. Could this lead to a difference in the ecological impact of EPATs in Portugal and Spain? This study contributes to existing knowledge by analyzing for the first time the environmental impact of EPAT and ER&D in Portugal and Spain in a comparative way. Another contribution of the study is that it is a pioneer study that analyzes the validity of LCC for Portugal and Spain using the FADL approach. For a sustainable future, it is important to comprehensively assess environmental sustainability. In this context, the LCC hypothesis enables the simultaneous analysis of income, air, water and soil pollution and the nature's response to this pollution. The study strengthens the modeling by analyzing the LCC hypothesis with two different indicators of technological progress (environmental patents and ER&D), because effective and green production through technological progress is a necessity for a sustainable future. With these novelties, the study is likely to open a new field of discussion in the field of environmental economics, both thematically and methodologically.

The second part of the study reviews the literature. The third part presents the data and the method. The fourth part discusses the results, and the fifth part concludes the study.

2. Literature review

In the literature section, the study presents studies that examine the ecological impact of patents and ER&D. Subsequently, studies on LCF (see e.g., [17,50]), and LCC (see e.g., [55]) are discussed.

2.1. Patents and environmental quality

Analyzing the environmental impact of patents is a current research topic. Researchers have generally considered the ecological impacts of patents as a whole (see e.g., [14]), but more recently some researchers have focused on EPAT. Jiang et al. [30] reported that EPAT mitigates CO_2 in BRICS nations. Ahmed et al. [3] noted that EPAT reduces EF in the G7 nations. Mahmood et al. [39] concluded that EPAT mitigates CO_2 and the EF in OECD nations. Abban et al. [1] found that patents reduce CO_2 in 29 EU countries. Javed et al. [29] revealed that EPAT mitigates EF in Italy. Aytun et al. [7] noted that patents have no impact on EF in 19 middle-income countries. Bergougui and Aldawsari [11] found that a positive and negative shock to EPAT attenuates EF in Algeria. Kahia and Omri [31] noted that both total patents and EPAT support ecological sustainability in Saudi Arabia. Pata et al. [49] reported that EPAT reduces CO_2 in Germany. Radulescu et al. [52] employed the cross-sectional ARDL and found that EPAT improves LCF in six developing countries. Tiwari and Mohammed [58] concluded that EPAT promotes environmental progress in 11 OECD nations. Hypothesis regarding this section: H_a: EPAT contributes to the improvement of environmental quality.

Studies on PAT, EPAT and environmental quality show different results depending on the country. The results may also vary depending

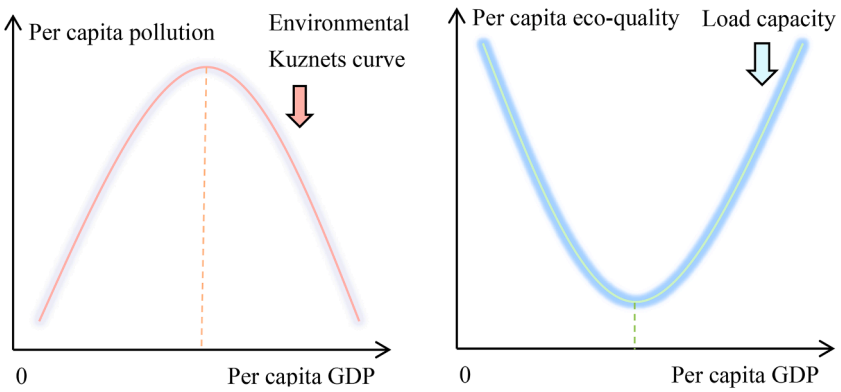

Fig. 1. Comparison between EKC and LCC.

on the environmental indicators one focuses on, and therefore the relationship between EPAT and ecological progress is still a controversial research topic.

2.2. R&D on energy and environmental quality

The environmental impact of ER&D expenditures is being studied by researchers from various perspectives. Since fossil fuels are carbon-intensive environmental pollutants, there is a need to increase R&D expenditures on energy efficiency and clean energy. Opinions differ on whether this increase will bring environmental benefits. Álvarez-Herránz et al. [5] noted that renewable ER&D decreases GHG in 28 OECD nations. Koçak and Ulucak [36] showed that ER&D has no positive effect on the environment for nine OECD nations. Shao et al. [56] reported that ER&D reduces CO_2 in the USA. Guzowska et al. [23] noted the same results as Shao et al. [56] for the EU region. Herzer [26] and Yang et al. [65] noted that renewable ER&D mitigates CO_2 in the G7 nations. Altintas and Kassouri [4] concluded that renewable ER&D mitigates carbon footprint in 28 OECD countries. Hayat et al. [25] revealed that renewable ER&D mitigates CO_2 in OECD countries. Uche et al. [60] concluded that renewable and nuclear ER&D decrease CO_2 in G10 nations. Hypothesis regarding this section: H_a: ER&D affects ecological quality.

The ecological impact of ER&D may vary depending on the total and renewable energy considerations, the focus country or group of countries and the environmental indicator. The use of ER&D that focuses on clean energy generally plays a pro-environmental role, but the insignificance of ER&D implies that countries are not spending enough energy-related ER&D. For this reason, the ER&D-environment relationship is an area that still needs to be explored.

2.3. EKC and LCC related studies

The EKC is one of the main topics attracting the attention of environmental economists, and its analysis has recently become the focus of attention along with global warming. Researchers continue to evaluate the validity of the EKC across various countries. Ben Jebli and Kahia [10] employed panel data estimators and supported the EKC for 65 countries. Kahia et al. [34] and Kahia et al. [32] employed time series estimators and noted that the EKC is not valid for Saudi Arabia. Boufateh et al. [12] utilized the ARDL and confirmed the EKC for Tunisia. Emir and Karlilar [15] confirm the EKC for the Turkish economy. Abbas et al. [2] employed the cross-sectional ARDL and verified the EKC for 118 Chinese cities.

Some studies also focused on Portugal and Spain. Roca et al. [53] examined six different environmental pollution indicators for Spain using regression analysis and determined an EKC-type relationship only for sulfur dioxide. Ordás Criado [44] employed non-parametric regressions and concluded an EKC-type relationship for carbon monoxide, CO_2, non-methane volatile organic compounds, and methane in 48 Spanish provinces. Esteve and Tamarit [18] employed the Arai–Kurozumi–Kejriwal co-integration and could not verify the EKC for Spain. Shahbaz et al. [54] used the ARDL and reported that EKC is valid for Portugal. Balaguer and Cantavella [8] used the ARDL and supported the EKC for Spain. Balsalobre-Lorente and Shahbaz [9] performed fixed effects and confirmed the EKC for GHG emissions in Spain. Besides, some researchers have comparatively analyzed the validity of the EKC only in Portugal and Spain. Moutinho et al. [42] found an inverted N-shaped relationship between GDP and CO_2, Moutinho et al. [41] emphasized that the EKC is not valid on a sectoral basis.

While discussions on the validity of the EKC continue, Pata [46] introduced the empirically analyzable LCF into the literature, and subsequently Dogan and Pata [13] suggested the LCC and stated in their seminal study that the LCC hypothesis is valid for the G7 countries. Huang et al. [27] identified an N-shaped relationship between LCF and GDP per capita for India. Pata et al. [48] could not confirm the LCC for Germany. Erdogan [16] found that the LCC is invalid for South African nations. Wu et al. [63] verified the LCC for fast-growing countries. Yang et al. [64] proved the validity of the LCC for the BRICS nations. Wang et al. [61] supported the LCC for Asian economies. The literature indicates that the findings about the validity of EKC and LCC vary by country.

2.4. Research gap

Although many analyzes have been conducted for EKC and LCC in previous studies, there are several research gaps specifically for Spain and Portugal. A limited number of studies in the literature have comparatively examined the validity of EKC in Portugal and Spain (see e.g., [41,42]). However, these studies did not consider Fourier transforms, and other Spanish and Portuguese studies are also methodologically outdated. In addition, no study has yet analyzed the validity of the LCC for Spain and Portugal using time series methods. Another research gap is the lack of a study analyzing the impact of environmental patents and ER&D on the LCF for Spain and Portugal. The fact that the environmental impact of ER&D for Spain and Portugal has not been comparatively analyzed is an important research gap, as the development of energy-related technologies can play a key role in carbon

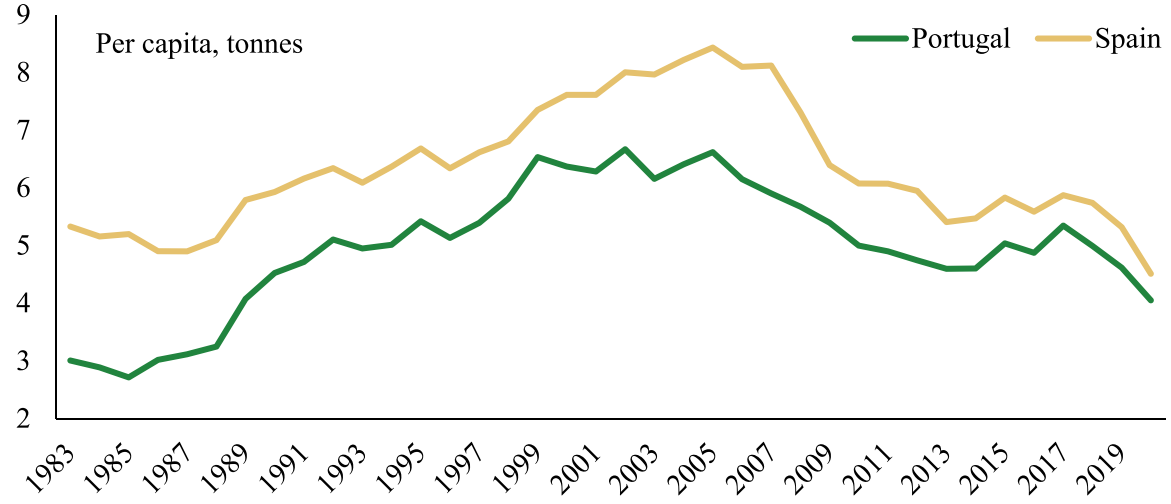

Fig. 2. CO_2 emissions in Portugal and Spain from 1983 to 2020
Source: Our world in data [45].

neutrality by ensuring energy efficiency and renewable energy development. This study aims to fill the relevant research gaps on the impact of environmental patents, ER&D and GDP on the LCF using the FourierADL approach for Portugal and Spain under LCC.

3. Data and methodology

3.1. Data and model

In the study, the validity of LCC and EKC for Portugal and Spain is comparatively analyzed using data for the period 1983–2020. The dependent variables are CO_2 and LCF, the independent variables are GDP, ER&D and EPAT, and each variable has 38 observations. Information on the variables, sources and calculation units can be found in Table 1.

The study data do not include any human participants and are sourced from the web addresses of official institutions as primary data. To test the effects of economic progress, environmental patents and ER&D on environmental conditions, the study uses Eq. (1).

$$\text{Ecological indicators}(CO_2 \text{ or LCF}) = f(\text{GDP}_t, \text{GDP}_t^2, \text{ER\&D}_t, \text{REC}_t) \quad (1)$$

The study then utilizes the logarithmic Eqs. (2) and (3) to analyze the LCC and EKC, respectively, to calculate the elasticities.

$$\ln CO_{2t} = \delta_0 + \delta_1 \ln GDP_t + \delta_2 \ln GDP_t^2 + \delta_3 \ln ER\&D_t + \delta_4 \ln EPAT_t + e_t \quad (2)$$

$$\ln LCF_t = \mu_0 + \mu_1 \ln GDP_t + \mu_2 \ln GDP_t^2 + \mu_3 \ln ER\&D_t + \mu_4 \ln EPAT_t + w_t \quad (3)$$

In Eq. (2), δ_1 should be positive and δ_2 negative for the validity of EKC, while in Eq. (3), μ_1 should be negative and μ_2 positive for the validity of LCC. Therefore, the LCC can also be characterized as an inverted EKC. Since Grossman and Krueger [22], there have been debates about the validity of the EKC. However, the LCC is a relatively new hypothesis whose validity has not yet been tested in many countries. Many studies have focused on analyzing the validity of the LCC hypothesis and have not reached a consensus. Yurtkuran and Pata [66] defend the validity of the LCC for Canada, but Pata et al. [48] emphasize that the corresponding hypothesis is not valid for Germany.

There is no consensus on the ecological impact of ER&D. Koçak and Ulucak [36] found that ER&D has no influence on ecological quality, while Shao et al. [56] emphasized that ER&D contributes to CO_2 minimization. It has been generally determined that the effect of environmental patents on pollution reduction is positive (see e.g., [49]), and therefore the coefficient μ_3 may be positive. The descriptive statistics are presented in Table 2.

The data in Table 2 show that Spain's economy is larger than Portugal's and that Spain's expenditure on environmental patents and ER&D is higher than Portugal's. The most volatile variable for Portugal and Spain is EPAT. This shows that environmental patents in the two countries follow a fluctuating pattern over time. The GDP series in Portugal and the ER&D series in Spain do not show a normal distribution. The Jarque-Bera test statistics indicate that the other series have a normal distribution.

3.2. Methodology

The study follows a six-stage strategy of empirical analysis and discussion of the results. The analysis strategy of the study is illustrated visually in Fig. 5.

After the descriptive statistical analysis, the ADF (Dickey and Fuller, 1981) and the DF-GLS (Elliott et al., 1996) unit root test are applied in a second step. In the third step, for the co-integration analysis, the FADL by Banerjee et al. (2017) is used. In the fourth and fifth steps, the validity of the EKC and LCC is analyzed for Portugal and Spain, respectively, by adding Fourier transformations to the FMOLS estimator of Phillips and Hansen (1990). In the last step, the results for Portugal and Spain are discussed comparatively and proposed solutions for the environment are presented. In the study, the unit root tests and the optimal lag lengths in the FADL approach are determined by the Schwarz information criterion. The FADL test ensures that gradually changing economic and environmental events are taken into account in the context of structural breaks. The FADL test proposed by Banerjee et al. (2017) captures breaks of unknown time, structure and number with Fourier transforms and includes them in the modeling and does not use dummy variables. In the first stage, the FADL test relaxes the assumption that the intercept (d(t)) does not change over time by relying on Fourier transforms as in Eq. (4).

$$d(t) = a_0 + a_1 sin\left(\frac{2\pi kt}{T}\right) + a_2 cos\left(\frac{2\pi kt}{T}\right) \quad (4)$$

where α_0 is the constant term, k is a specific frequency, and t is the trend. Finally, by including the modified $d(t)$ in the analysis, the FADL modeling is created as in E. (5).

$$\Delta y_{1t} = d(t) + \sigma_1 y_{1,t-1} + \gamma' y_{2,t-1} + \varphi' \Delta y_{2t} + u_t \quad (5)$$

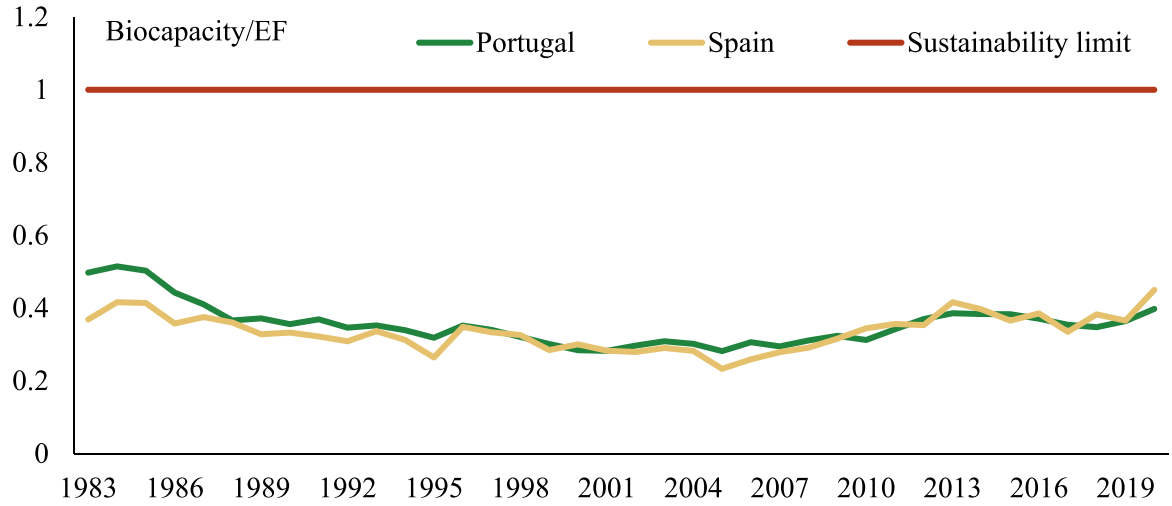

Fig. 3. LCF and sustainability in Portugal and Spain
Source: GFN [21].

In Eq. (5), y_2 involves the explanatory variables. Following Christopoulos and Leon-Ledesma (2011), the study allows fractional frequencies for optimal k selection ranging from 0.1 to 5. In the last stage, the null hypothesis of no co-integration is analyzed by calculating the FADL test statistic ($t_{ADL} = \frac{\widetilde{\sigma_1}}{standanrt\ error\ of\ \widetilde{\sigma_1}}$).

The FADL approach incorporates Gallant's [20] trigonometric functions from with flexible functional forms into the co-integration analysis and thus enables the modeling of structural breaks with unknown time and structure. The FADL approach offers advantages over the standard ARDL approach due to the modeling of structural breaks and the consideration of non-linear structures. The relationships between income and environment can be affected by many structural changes such as economic crises, pandemics and wars. Therefore, the study aims to provide effective results by using the FADL approach in examining the validity of the LCC.

4. Empirical results and discussion

The study uses unit root tests as a prerequisite to test the applicability of Fourier ADL and FMOLS and reports their results in Table 3.

The results of the ADF and DF-GLS unit root test show that all series are stationary at the first difference, I(1). Since all series are I(1), the co-integration analysis between environmental quality, GDP, EPAT and ER&D can be analyzed using the FADL approach. The FADL results are presented in Table 4.

The t^F_{ADL} statistics indicate that there is co-integration between the series at the 1 % level for LCF. In the models where CO_2 is the dependent variable, there is a co-integration relationship between the series at a level of at least 5 %. Therefore, the validity of the LCC and EKC hypotheses can be tested comparatively for Spain and Portugal. To this end, the study estimates the FMOLS approach using Fourier functions and reports the results for EKC in Table 5.

In Table 5, SSIN and CCOS are statistically significant for both countries, indicating that the addition of Fourier terms to the FMOLS estimator is compatible. As for the GDP and GDP^2 coefficients, the EKC hypothesis is shown to be valid for Spain and Portugal. The validity of the EKC hypothesis states that countries above a certain per capita income have financial strength, environmental awareness and investment in renewable energy that can reduce environmental degradation and thus minimize CO_2 emissions. In 2022, Spain and Portugal have a per capita income of USD 27 thousand and Portugal of USD 22 thousand, and the average GDP per capita in the world is USD 11 thousand [62]. These countries, whose GDP per capita is twice as high as the world's average GDP per capita, have it in their power to combat climate change by diverting financial resources to clean energy resources, green technologies and environmental awareness programs within the EKC hypothesis. In contrast to Li et al. [37], the validity of the EKC is in line with Pata and Karlilar [47].

ER&D is statistically insignificant for both Portugal and Spain. This indicates that ER&D expenditures does not effectively contribute to CO_2 mitigation. In contrast to Guzowska et al. [23] and Shao et al. [56], this result is in line with Koçak and Ulucak [36]. Although Portugal spends

Table 1
Definition of the variables.

Series	Symbol	Measurement	Reference
Carbon emissions	CO_2	tonnes	Our World in Data [45]
Load capacity factor	LCF	EF/biocapacity	GFN [21]
Economic growth	GDP	Per capita, constant 2015 USD	World Bank [62]
R&D expenditures on Energy	ER&D	Total Energy R&D budgets, constant 2022 USD	IEA [28]
Environmental patents	EPAT	Number of patent applications to the EPO	OECD [43]

Table 2
Descriptive statistics.

Portugal					
	lnLCF	lnGDP	lnEPAT	lnER&D	$lnCO_2$
Mean	−1.046	9.734	3.677	2.105	1.576
Median	−1.050	9.837	3.730	1.843	1.610
Maximum	−0.664	9.981	5.663	4.339	1.897
Minimum	−1.266	9.282	0.693	0.338	0.998
Std. Dev.	0.152	0.199	1.364	1.258	0.247
Skewness	0.821	−1.030	−0.324	0.440	−0.908
Kurtosis	3.408	2.876	1.907	1.984	2.999
Jarque-Bera	4.534	6.744	2.557	2.863	5.228
Probability	0.103	0.034	0.278	0.238	0.073
Spain					
Mean	−1.102	10.009	6.499	4.727	1.831
Median	−1.096	10.106	6.813	4.661	1.805
Maximum	−0.798	10.243	7.529	6.105	2.131
Minimum	−1.456	9.608	4.392	4.099	1.506
Std. Dev.	0.148	0.192	0.945	0.446	0.167
Skewness	−0.169	−0.704	−0.684	1.399	0.209
Kurtosis	2.564	2.227	2.190	4.854	2.111
Jarque-Bera	0.481	4.088	4.007	17.854	1.528
Probability	0.785	0.129	0.134	0.000	0.465

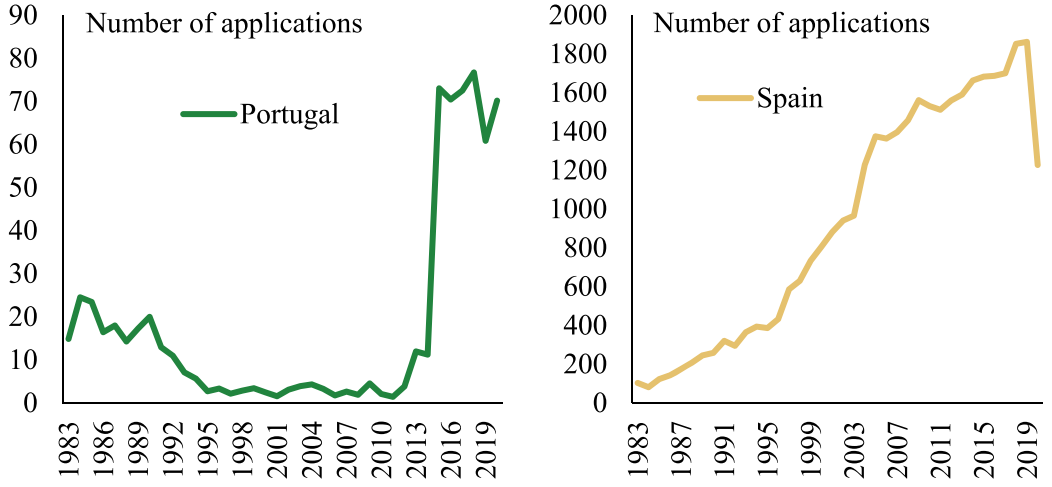

Fig. 4. Environmental patent applications
Source: OECD [43].

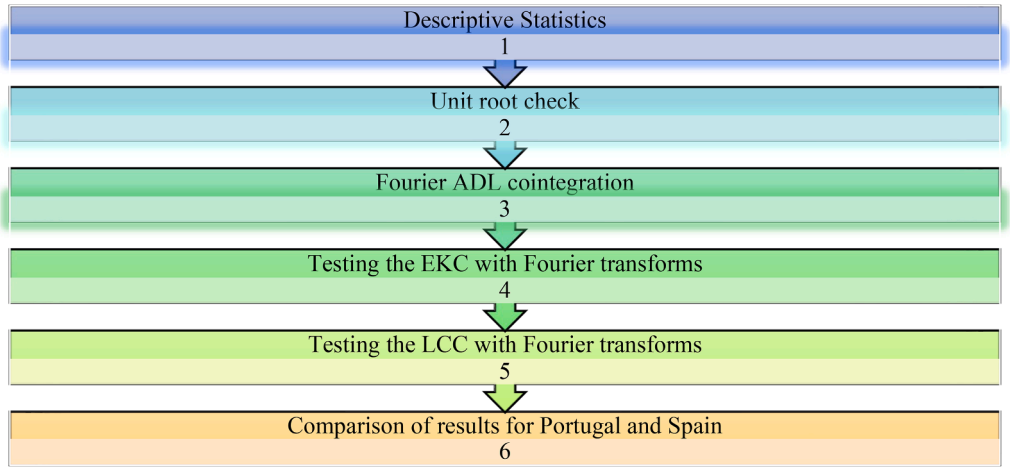

Fig. 5. Analysis flow chart.

USD 81 million and Spain USD 730 million on ER&D in 2022, the Portuguese and Spanish ER&D values are quite low compared to the USD 1975 million in France and the USD 1501 million in Germany in the same year [28]. This shows that Portugal and Spain are not using ER&D sufficiently and effectively. In other words, ER&D expenditures in these two countries is too low to achieve measurable environmental effects. Moreover, time and budget are needed to implement effective and efficient ER&D. In view of this, the Spanish and Portuguese governments should allocate more financial resources to this area in order to benefit from the technique and innovative effects of ER&D expenditures and achieve green development.

EPAT has a CO_2 -reducing effect for Spain and Portugal. In contrast to Töbelmann and Wendler [59], the pollution-reducing role of environmental patents can be attributed to Mongo et al. [40], and Hao et al. [24]. Environmental patents help to spread wind, solar and similar renewable resources and use them more effectively. In this context, it is a reasonable realization that EPAT supports a better ecosystem.

Finally, the study analyzes the validity of the LCC hypothesis for Spain and Portugal and presents the findings in Table 6.

The outcomes of the analysis illustrate that the LCC is valid for Portugal and Spain. In contrast to Erdogan [16], the validity of the LCC agrees with Wu et al. [63]. The validity of the LCC hypothesis shows that the increase in GDP per capita in Portugal and Spain can simultaneously lead to an augment in biocapacity and a reduction in EF. When EKC and LCC are evaluated together, the upsurge in GDP per capita is an important tool to reduce CO_2 and increase LCF for Portugal and Spain. ER&D has no significant impact on the LCF for both countries, while EPAT plays a supporting role in increasing the LCF. The findings of this study suggest that Portugal and Spain can effectively use environmental patents to increase the LCF. The final findings of the study are shown in Fig. 6.

Table 3
Unit root outcomes.

	ADF		DF-GLS	
Variables	Test-stat	lag	Test-stat	lag
Spain				
lnLCF	−1.780	0	−1.338	1
$\ln CO_2$	−0.417	0	−0.982	1
lnGDP	−2.232	1	−1.577	1
lnEPAT	−1.868	4	−0.990	1
lnER&D	−2.325	3	−1.152	3
ΔlnLCF	−7.765*	0	−5.633*	0
$\Delta\ln CO_2$	−3.481**	0	−3.301*	0
ΔlnGDP	−2.232	1	−2.095**	1
ΔlnEPAT	−5.455*	0	−2.808*	0
ΔlnER&D	−6.374*	0	−5.858*	0
Portugal				
lnLCF	−2.271	0	−1.186	0
$\ln CO_2$	−1.855	0	−1.030	0
lnGDP	−2.302	8	−1.577	1
lnEPAT	−1.652	1	−0.355	0
lnER&D	−0.798	0	−0.918	0
ΔlnLCF	−4.864*	0	−4.444*	0
$\Delta\ln CO_2$	−4.263*	0	−3.921*	0
ΔlnGDP	−3.923*	3	−2.027**	0
ΔlnEPAT	−7.695*	0	−2.464**	1
ΔlnER&D	−6.218	0	−5.673*	0

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

The summarized results indicate that both hypotheses are valid for both countries, that ER&D expenditures are environmentally ineffective, and that EPAT support an improvement in ecological quality. In line with the findings, the Portuguese and Spanish governments should support an increase in GDP per capita and environmental patents to improve ecological quality. Technological progress enables the development of LCF and CO_2 reduction through the channel of environmental patents. This situation shows that only environmental patents contribute to sustainable development for the first research question. Regarding the second research question, the validity of EKC and LCC shows that the Portuguese and Spanish governments can have a society with increased environmental awareness with simultaneous income growth and environmental investment, while developing financial resources, thus achieving the goals of carbon neutrality and increasing LCF.

For future development, the governments of Spain and Portugal should take measures to increase the LCF, taking into account the positive effects of environmental patents and income growth. Future sustainable development requires that environmental and economic development be achieved together, and to this end technological progress must be supported by governments. In this context, Portugal and Spain can promote future sustainable development by facilitating the financing of environmental patents that increase energy efficiency, expand waste management and encourage the use of clean energy with income growth.

5. Conclusion and policy recommendations

5.1. Conclusion

Advances in environmental technology have recently been recognized as one of the most important tools for solving environmental problems. Analyzing new variables has become popular over time in the fight against environmental problems, and researchers have recently brought LCF to the forefront. LCF provides an environmental assessment through the supply and demand channels and fully reflects the criterion

Table 4
The FADL results.

Dependent variable		$t^{F}_{ADL}(\hat{k})$	$\hat{k}$	FADL	AIC	1 % CV	5 % CV
LCF	Spain	−7.754*	1.90	(3,4,4,4)	−3.733	−5.301	−4.612
	Portugal	−6.320*	1.50	(1,2,2,2)	−2.560	−5.335	−4.678
CO_2	Spain	−4.899**	0.20	(3,1,2,2)	−3.508	−5.412	−4.782
	Portugal	−6.391*	1.30	(1,2,2,1)	−3.639	−5.304	−4.523

Note: CV: critical value. See the notes for Table 3.

Table 5
FMOLS with Fourier transforms for EKC hypothesis.

Variables	coefficients	t-stat.	p-value
Spain			
lnGDP	46.229*	5.767	0.000
$lnGDP^2$	−2.310*	−5.859	0.000
lnER&D	0.060	1.081	0.288
lnEPAT	−0.050**	−2.551	0.016
C	−232.421*	−5.738	0.000
SSIN	−0.174*	−15.311	0.000
CCOS	−0.178*	−9.412	0.000
Portugal			
lnGDP	29.534*	9.387	0.000
$lnGDP^2$	−1.473*	−8.952	0.000
lnER&D	0.009	1.532	0.135
lnEPAT	−0.055*	−4.637	0.000
C	−146.036*	−9.702	0.000
SSIN	−0.124*	−11.592	0.000
CCOS	−0.083*	−10.335	0.000

Note: See the notes for Table 3.

of sustainability. The relationship between LCF and GDP is theoretically based on the LCC hypothesis. In this context, the study tests for the first time the validity of the LCC for Portugal and Spain in the context of EPAT and ER&D. The study uses the FADL approach and also examines the validity of the EKC in its analysis. The findings of the study indicate that EKC and LCC are valid for Portugal and Spain. EPAT provides environmental benefits for both countries, but ER&D has no significant impact on CO_2 or LCF. These findings have important policy implications for carbon neutrality targets.

5.2. Policy recommendations

The validity of the LCC and EKC hypotheses for Portugal and Spain shows that per capita GDP growth ultimately improves environmental conditions. For this reason, the Portuguese and Spanish governments should channel the financial opportunities arising from the increase in GDP per capita into eco-friendly areas. The promotion of environmental patents is a good option for this. EPAT is effective in both reducing CO_2 and increasing the LCF, while ER&D has no significant impact on environmental indicators. Given this fact, the Portuguese and Spanish governments should provide financial subsidies to companies to encourage the development of wind turbines and solar panels, as well as environmental patents that increase energy efficiency. In addition, policy makers should offer tax exemptions, the provision of machinery and equipment, and favorable credit facilities to companies that file patents related to carbon capture technologies. The Portuguese and Spanish governments need to review ER&D expenditures. In this area, the governments should increase spending on clean ER&D and minimize the funding transfer to fossil fuels. Thus, by increasing the LCF, Spain and Portugal should aim for an LCF value above 0.50, at least in the short term, and have a sustainable ecosystem with LCF values above "1″ in the long term.

Table 6
FMOLS with Fourier transforms for LCC hypothesis.

Variables	coefficients	t-stat.	p-value
Spain			
lnGDP	−47.424*	−3.604	0.001
$lnGDP^2$	2.267*	3.412	0.001
lnER&D	0.026	0.608	0.547
lnEPAT	0.433*	4.376	0.000
C	243.342*	3.722	0.001
SSIN	−0.058*	−2.881	0.007
CCOS	−0.028	−0.871	0.390
Portugal			
lnGDP	−35.591**	−2.517	0.017
$lnGDP^2$	1.811**	2.448	0.020
lnER&D	−0.023	−1.058	0.298
lnEPAT	0.078***	1.748	0.090
C	173.356**	2.563	0.015
SSIN	0.126*	3.630	0.001
CCOS	−0.075**	−2.490	0.018

Note: See the notes for Table 3.

ER&D is a long-term process and in order for it to contribute to the environment, Portugal and Spain need to take various measures. In this context, the governments of the two countries can provide financial subsidies to companies that promote the development of clean energy technologies. In addition, technological progress can be accelerated by offering tax incentives to entrepreneurs who disseminate green innovations in the energy sector. To this end, the financial institutions of Spain and Portugal can benefit from the funds made available by the EU to finance ER&D expenditures by promoting the development of clean technologies under REPowerEU. The EU has decided to make funds available to member states under the Recovery and Resilience Facility (RRF) until December 2026 [19]. Spain and Portugal can benefit from the RRF fund by supporting environmentally friendly technologies.

5.3. Limitations and future research

The study has some limitations, the first of which is related to the data. As the ER&D data for Spain ends in 2020, 38 observations were included in the study. Future studies could provide comprehensive information on the validity of the LCC hypothesis with additional observations. The second is that the study only focuses on environmental patents and ER&D. This limitation is related to the Fourier ADL, as the corresponding method allows an analysis with a maximum of four independent variables. Future studies could discuss the determinants of LCF with more variables as part of methodological improvements. The third limitation is that the study considers all ER&D, as no data on R&D expenditure in the renewable energy sector is available for Portugal. If data are available in the future, this study can be repeated in the context of renewable ER&D expenditures to check the robustness of the findings. Theoretically, the study proposes to extend the sustainability implications of the LCC hypothesis by considering and analyzing the effects of technological progress for different countries. Analytically, the study considers Fourier transforms and structural breaks but neglects the frequency domain properties of the series. Therefore, future studies can comparatively analyze environmental sustainability in Spain and Portugal using econometric methods based on wavelet transforms. Another suggestion of the study relates to technology indicators. Future studies can examine the effects of different R&D expenditures such as energy efficiency, clean energy and energy storage on the LCF for Spain and Portugal under the LCC when data are available. Furthermore, future studies can add to the existing knowledge by analyzing the

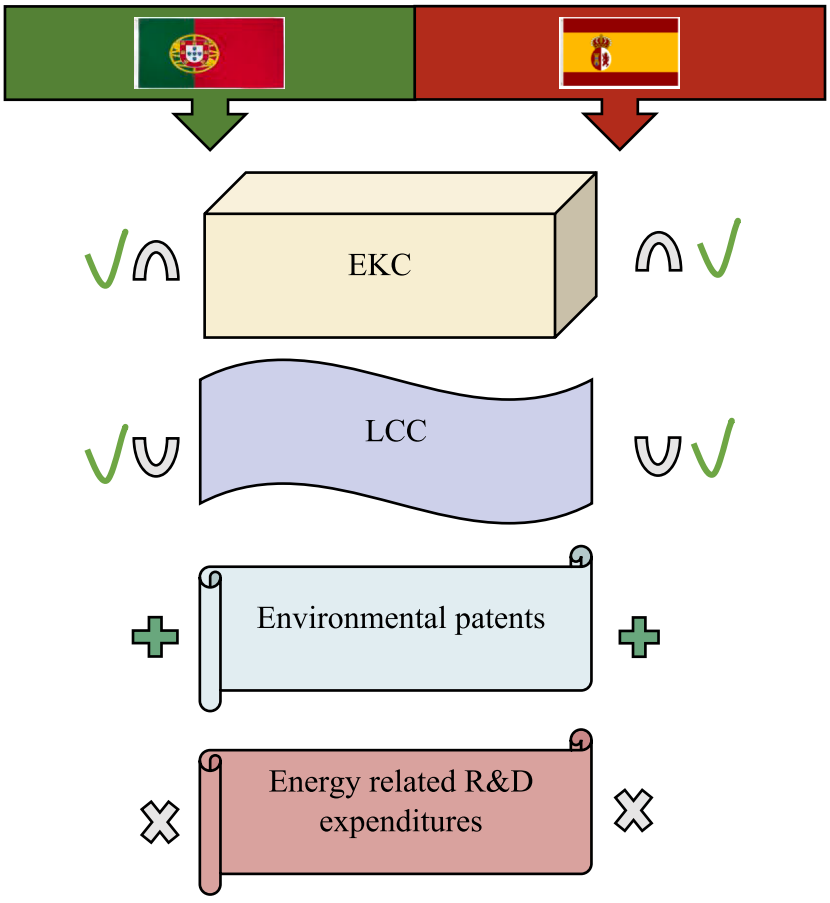

Fig. 6. Summary of the LCC and EKC models.

environmental impact of recycling, clean fuels, and green transport related EPAT in the context of the LCC. In this way, the LCC hypothesis and the knowledge about the environmental qualities of Spain and Portugal can be extended.

Funding statement

This research was not funded by any agency.

Ethics approval

Ethical approval is not required for this study, as the data used does not include human participants, human data, or human tissue.

CRediT authorship contribution statement

Ugur Korkut Pata: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

The data and materials used in this study are available on request from the corresponding author.

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