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The role of renewable and nuclear energy R&D expenditures and income on environmental quality in Germany: Scrutinizing the EKC and LCC hypotheses with smooth structural changes

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HIGHLIGHTS

- Examines the environmental impact of renewable and nuclear energy R&D expenditures.
- Focuses on Germany using three environmental indicators from 1974 to 2018.
- Nuclear energy-related R&D expenditures are not effective on the environment.
- Renewable energy-related R&D expenditures reduce CO_2 emissions.
- The EKC hypothesis is valid, whereas the LCC hypothesis is not.

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ABSTRACT

This study analyzes the effect of renewable energy research & development (RRD) and nuclear energy research & development (NRD) expenditures on environmental quality by considering Germany's goal of achieving carbon neutrality until 2045. Hence, the study uses various environmental indicators (carbon dioxide (CO_2) emissions, ecological footprint-EF, and load capacity factor-LCF) to investigate the effects of RRD and NRD on the environmental quality controlling also a gross domestic product (GDP) and test the validity of the environmental Kuznets curve (EKC) and recently proposed load capacity curve (LCC) hypotheses. Also, the study includes yearly data from 1974 to 2018, uses fractional frequency Fourier autoregressive distributive lag (FADL) based FMOLS approach as the main model, and applies FADL based DOLS approach and Fourier wavelet causality test for the robustness. The empirical results reveal that (i) the explanatory variables have a cointegration link with CO_2 emissions and EF; (ii) the EKC hypothesis is valid for Germany, while the LCC hypothesis is invalid; (iii) RRD expenditures are effective only in reducing CO_2 emissions; (iv) RRD and NRD expenditures have no significant effect on the EF. Considering the results, German policymakers could utilize RRD more effectively and efficiently to improve environmental quality and reduce the EF. In this way, Germany could achieve its carbon neutrality goal until the middle of the century by benefiting from RRD facilities.

Abbreviations: **IEA**, International Energy Agency; **KRLS**, Kernel-Based Least Squares; **LCC**, Load Capacity Curve; **LCF**, Load Capacity Factor; **LM**, Lagrange Multiplier; **MMQR**, Method of Moment Quantile Regression; **NARDL**, Non-linear ARDL; **NRD**, Nuclear Energy Research & Development Expenditures; **NUC**, Nuclear Energy Consumption; **OECD**, Organisation for Economic Co-operation and Development; **REN**, Renewable Energy Consumption; **REN21**, Renewable Energy Policy Network for the 21st Century; **RD**, Research and Development; **RRD**, Renewable Energy Research & Development Expenditures; **SDG**, Sustainable Development Goal; **TVAR**, Threshold Vector Autoregression; **UK**, United Kingdom; **US**, United States; **ZA**, Zivot-Andrews; **2SIV**, Two-Stage Instrumental-Variables.

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1. Introduction

SDG-8 highlights the importance of promoting sustainable economic development through technological innovation and diversification. Economic growth is closely linked to the development of countries, the success of governments in creating better living conditions, and increasing the overall well-being of societies [1]. As economic issues have been top priorities for countries and people, the world has been facing global warming recently due to increasing anthropogenic greenhouse gas emissions from human activities [2]. Hence, studies focusing on environmental quality have been increasing as a result of developing public interest in the environment while the world is facing various negative environmental issues, such as decreasing biocapacity, increasing environmental pollution, deteriorating environmental quality, and accelerating climate change [3].

In the literature, various environmental indicators are used for empirical examination. Earlier studies used CO_2 emissions [4,5], while later studies considered the EF as an indicator for environmental degradation [6–8]. Also, after the theoretical study of [9] and the leading empirical study of [10], recent studies have included the LCF as the most comprehensive environmental quality indicator through considering demand as well as supply sides [11–14].

In the current studies, the effect of income (i.e., economic growth) has been intensively investigated following the study of [15] known as the EKC hypothesis [16]. Besides, the LCC hypothesis has been recently proposed by [12,13], which focuses on the environmental quality perspective rather than environmental degradation. The EKC and LCC hypotheses state that as income increases, environmental conditions deteriorate in the first stage of economic progress and that after a certain income level is passed, environmental quality improves with people's ecological awareness, technological development, and green energy utilization. In addition to the EG, energy consumption is frequently considered in uncovering the environment [17] because energy consumption is the major cause of greenhouse gas emissions according to data from [18,19]. Accordingly, various studies have explored the effect of fossil fuel energy [20], renewable energy [21], and nuclear energy [22] on the environment.

By considering the effects of energy on the environment, countries have paid more attention to technological developments regarding energy consumption. In this context, RD activities are highly critical for developing new and efficient ways. RD activities are the most possible way in searching for advancing new low-carbon energy technologies. In this way, RD activities can be helpful to decrease energy consumption amount by harvesting more energy from the same raw materials as well as enabling sustainable economic growth by using much more clean energy [23]. Thus, RD activities are strategic weapons for countries to achieve SDG-7 (clean energy) and SDG-13 (climate action), which are important to become carbon–neutral economies. Therefore, countries have allocated much bigger budgets for RD activities by recognizing the critical role of RD activities on the economies, energy consumption, energy efficiency, energy saving, and environmental quality and recent studies have focused on the RD expenditures in turn [24].

According to [25]), the US, Japan, and Germany are the leading countries that have allocated higher public budgets for energy-related RD activities. Among these countries, Germany, as a major industrialized country, has environmental damage and an ecological deficit [26]. Moreover, Germany has recently faced an energy crisis and the expansion of nuclear energy has been proposed as an alternative to address such a crisis [27]. Apart from other leading R&D expending countries, the German approach to the environmental issue does not seem to enable the usage of high nuclear energy consumption except for benefitting from exiting capacity for a while. Even if such a case happens, it may only be temporary and not a long-run option for Germany. Due to the high level of RD expenditures and environmental pollution, it is important to research the effect of RD expenditures on the environment for the German case. The outcomes of the German case can shed light on the effects of energy-related RD expenditures on environmental quality for other high RD investing countries with similar economic and environmental characteristics as well as all other developing countries in protecting environmental quality by benefitting from RD expenditures. Thus, energy-related RD activities, especially RRD and NRD, are of great importance for Germany. That is why because renewable and nuclear energy have a big share in electricity generation in Germany, which is 50.4 %, 53.3 %, 49.6 %, and 46.8 % for the years 2019, 2020, 2021, and 2022, respectively [28]. Specifically, renewable energy has a higher share (40.4 %) than nuclear energy (6.4 %) in electricity in 2022, which implies that RRD can be highly influential on the environment concerning the NRD. Hence, RD expenditures in renewable energy and nuclear energy are highly crucial from the classical RD investments from the economy, energy, and environmental perspectives because activities, which do not consider the energy-environment-pollution nexus, cannot be beneficial [29]. In this point, Annex 1 shows the progress of the environmental indicators, EG, RRD, and NRD expenditures.

As Annex 1 presents, per capita CO_2 emissions in Germany are declining, the EF is higher than biocapacity, and the LCF is below the critical limit, which is 0.32 in 2018. This situation presents that current environmental conditions are unsustainable in Germany. Also, EG has an increasing trend in Germany with a corresponding income per capita of ~$43,000. Moreover, Germany has allocated a significant RRD, which have increased to $0.5 billion. However, NRD have steadily declined, which is related to the phase-out policy of nuclear power plants in Germany. Overall, RRD have had an increasing trend on average over the years, whereas NRD have had a declining trend since 1982. The current environmental condition of Germany represents the severe pressure and need for various mitigating factors, such as technological innovations and RD activities. Against the backdrop, it can be questioned whether Germany can increase its environmental quality by stimulating RD expenditures on renewable and nuclear energy. The main objective of this study is to answer this research question.

In the literature, although some studies include Germany in uncovering environmental quality [30–33], no study has focused on the role of renewable and nuclear energy RD expenditures in achieving carbon neutrality for the German case. Moreover, the studies in the literature have not applied empirical research by applying fractional frequency-based approaches and using the latest available data for the German case, which can be evaluated as a literature gap. Hence, considering the defined literature gap, this study handles the German case and examines the effect of RRD and NRD expenditures on the environment by controlling also income. This study searches answers following questions: (i) do RRD and NRD improve environmental quality? RD activities for energy are expected to contribute to the environment in high technology and RD investing countries, such as Germany; (ii) are the EKC and LCC hypotheses valid for Germany? Since Germany is a developed country, it is important to question the validity of the EKC and LCC hypotheses and the use of income as an environmental regulator.

This study provides contributions to the literature by first attempting to uncover the effects of RRD and NRD expenditures on the environment in Germany. For this purpose, the study includes various environmental quality indicators (CO_2 emissions, EF, and LCF) simultaneously in the empirical investigation, considering the most comprehensive content for the environment. Second, the adoption of the FADL cointegration method with a fractional frequency for the empirical investigation allows researchers to model smooth structural shifts. The study empirically analyzes the environmental effects of RRD and NRD for the first time by considering smooth changes makes it novel. Energy policies, technological processes, and environmental effects require gradual processes, so it is important to consider smooth changes. Studies addressing the environmental effects of energy-related RD expenditures have not previously considered smooth changes by using Fourier approximations [34–40]. From a methodological point of view, this study differs from the current literature and can be beneficial in discussing policy inferences for Germany to achieve its carbon-neutrality goal in the context of SDGs 7, 8, 13.

Following the introduction, the Part II of the study includes a literature review, while Part III presents a theoretical and conceptual framework. Part IV explains the data, model, and empirical methods. Part V shows the empirical results including the discussion as well. Part VI contains the conclusions and policy inferences.

2. Literature review

Various studies have tried to analyze the effect of diverse factors on the environment. The pioneer studies, especially after the advent of the EKC hypothesis, have focused on the effects of income on the environment. For example, [41,42] define an inverted U-shaped association between income and various pollution indicators, such as deforestation, sulfur dioxide, and particulate matter. [43] find the same relation with income and four pollutants, namely nitrogen oxides, sulfur dioxide, particulate matter, and carbon monoxide. [44] also report the inverted U-shaped relation between income and CO_2 emissions. Subsequently, some recent studies have defended the validity of the EKC hypothesis for CO_2 emissions [45–49], while others reject it [50–52].

Empirical studies testing the EKC have also focused on the EF, which includes air pollution as well as water and soil problems. In this context, some of the studies analyzing EF, which has relatively higher content than CO_2 emissions, are in favor of the validity of the EKC [53], while others do not support this hypothesis [54–55].

In the field of environmental economics, the relationship between income and LCF is a topic that has recently attracted much attention. Unlike pollutant representatives (i.e., CO_2 and EF), the LCF can be classified as an environmental quality indicator because it includes both EF and biocapacity, which indicates the ability to cope with pressures on land and water within the LCF. Some recent studies have considered the LCF as the proxy of the environment in the examination of environmental quality. [10–11,56–60] are among the recent studies that have used the LCF for the US & Japan, South Africa, China, Turkey, ASEAN countries, Brazil, and Turkey, respectively. These studies mainly conclude that EG degrades environmental quality. [12,13] go one step further with the LCC hypothesis, which implies that income has a U-shaped effect on the environment. Both studies test the LCC hypothesis for the G7 countries and South Korea and confirm that EG is above a turning point that supports environmental quality. This confirms that income is an important tool for ensuring environmental quality.

In addition to income, the literature includes various studies on energy consumption [61] including renewable and nuclear energy. For instance, [62–66] determine the contributing effect of renewable energy in decreasing CO_2 emissions for China, 74 selected countries, Argentina, the US, and China, respectively. Similarly, [20,22,67,68] define that nuclear energy consumption supports the environmental quality in the US, India, Spain, and 9 Pacific countries, in order.

Apart from the income and energy consumption-related studies, several studies have included RD expenditures in the empirical model. However, studies including RD expenditures on renewable and nuclear energy are still limited. For instance, [34] reports that RD expenditures have a significant effect on environmental quality progress in 12 Europe countries. [69] examine 28 OECD countries considering both low-carbon and non-low-carbon energy technologies. [70] investigate 19 OECD countries using disaggregated RD expenditures in energy. They conclude that RD expenditures on fossil fuel energy have a rising effect on CO_2 emissions, whereas renewable energy RD expenditures have no effect. However, [71] employ linear and nonlinear ARDL models and conclude that RRD is not effective in reducing CO_2 emissions in the US. In contrast, [35] find that RRD and NRD expenditures have a reducing effect on CO_2 emissions in Japan. [72] investigate the OECD countries and find that Germany does not benefit from the environmental efficiency of energy-related RD expenditures. [73–74] confirm a decreasing effect of RRD on the EF for the G7 and OECD countries, respectively. Moreover, [32] determine a decreasing effect of environment-related RD on CO_2 emissions in the G7 countries.

Furthermore, [37] uses the NARDL model and states that positive shocks to NRD expenditures have a diminishing effect on CO_2 emissions in the UK. In contrast, [75] conclude that energy-efficient RD expenditures do not have a declining effect on CO_2 emissions in five selected countries. [36] find that RRD expenditures improve energy efficiency in the US using the Bayer-Hanck cointegration test. [12] confirm a supportive effect of RD activities on environmental quality in the G7 countries using the cross-sectional ARDL approach. [38] apply an interactive-fixed effects model and indicate that RRD expenditures improve environmental quality in 27 selected countries. [39] concludes that RRD expenditures reduce CO_2 emissions in the G7 countries by performing several panel data estimators. [40] find a similar pro-environmental role of RRD expenditures for the G7 countries. But, clean energy technologies are not effective on the environment in the US [76].

As a result, Table 1 reports a summary of the empirical literature.

In summary, literature includes limited studies about the effect of RD expenditures on the environment in different countries. Nevertheless, there is no study focusing on specifically on Germany. In the literature, although various econometric approaches have been performed (e.g., dynamic fixed effects, mean group, and pooled mean group for South American countries by [79]; CS-ARDL for 30 Sub-Saharan Africa countries by [80]; cross-panel ARDL for South Asian region by [81]), the Fourier-based approaches (e.g., FADL) have not been widely used. In the literature, various studies have used the FADL approach for various purposes. For example, [82] investigate the link between inflation and inflation uncertainty in Turkey. [83] test the determinants of electricity consumption in EU countries. [84] explore the effects of oil prices, tourism, and foreign direct investment on GDP in Turkey. [85] analyzes the effects of agriculture, globalization, and renewable energy on the EF for BRIC countries. [86] test the effect of globalization and income on the EF for EU countries. [87] investigate the effects of coal, solar, and

Table 1
Literature Summary.

Author	Countries	Period	Model	Result
[10]	US & Japan	1982–2016	Augmented ARDL	EG ↓ EQ
[12]	G-7	1986–2017	CS-ARDL, AMG	LCC valid
[13]	South Korea	1977–2018	ARDL	LCC valid
[20]	US	1973–2022	Dynamic ARDL, KRLS	NUC ↑ EQ
[22]	India	1971–2018	Dynamic ARDL	NUC ↑ EQ
[35]	Japan	1974–2017	NARDL	RRD ↑ EQ
[37]	UK	1974–2020	NARDL	NRD ↑ EQ
[38]	27 Selected	1980–2020	2SIV	RRD ↑ EQ
[40]	G-7	1985–2019	CS-ARDL	RRD ↑ EQ
[45]	64 Selected	1990–2014	AMG	EKC valid
[46]	G-7	1979–2019	Panel ARDL, Panel DH	EKC valid
[47]	Top Ten Manufacturing	1990–2020	MMQR	EKC valid
[54]	China	1965–2016	Fourier ARDL	EKC not valid
[56]	China	1981–2016	Dynamic ARDL	EKC valid
[57]	Turkey	1965–2017	Dynamic ARDL	EG ↓ EQ
[62]	China	1995–2012	Panel GC	REN ↑ EQ
[63]	74 Selected	1990–2015	Panel CR, Panel GC	REN ↑ EQ
[64]	Argentina	1970–2018	ARDL	REN ↑ EQ
[65]	US	1965–2018	BFGCiQ	REN ↑ EQ
[66]	China	1990–2020	ARDL, FMOLS, DOLS	RE ↑ EQ
[67]	Spain	1970–2018	TVAR, GC	NUC ↑ EQ
[68]	9 Pacific	1971–2014	DOLS, FMOLS	NUC ↑ EQ
[70]	19 OECD	2003–2015	GMM	RRD ≠ EQ
[71]	US	1985–2017	ARDL	RRD ≠ EQ
[74]	18 OECD	1984–2018	CS-ARDL	RRD ↑ EQ
[77]	India	1988–2018	Augmented ARDL	LCC valid
[78]	China	1992–2020	ARDL	EKC valid

wind energy sources on the EF in India. [88] explore the effects of energy consumption, financial development, income, and trade openness on CO_2 emissions in Finland. As can be seen, no study using the FADL approach has examined the environmental effects of RD expenditures and their renewable and nuclear energy types. Since technological events, such as RD, are gradual processes, the empirical analysis must also take smooth changes through Fourier terms into account. Given this literature gap, this study is the first attempt to show the effect of RRD and NRD expenditures on the environment in Germany by using three different environmental indicators.

3. Theoretical and conceptual framework

As is proposed theoretically by [15], the EKC hypothesis is based on three effects that describe an inverted U-shaped relationship between income and the environment. The first effect, namely the scale effect, states that increasing production stimulates environmental degradation. During this phase of production expansion, fossil fuels are used intensively and an increase in CO_2 emissions is inevitable. The second effect, the composition effect, characterizes the transformation of the economy. Economies undergo a three-stage development in the form of agriculture, industry, and services. While the environmental pressure increases during the transition from agriculture to the industrial sector, the service sector supports the development of environmental technologies and contributes to the improvement of environmental quality, as fewer fossil fuel is needed. Finally, the technique effect increases the production of green technologies by supporting RRD [71].

The LCC hypothesis, which has been proposed recently by [12–13], implies that there is a U-shaped relationship between income and environmental quality. The LCC hypothesis focuses on the LCF indicator, which considers anthropogenic environmental pressures and environmental supply opportunities. [9] first introduced the LCF to the literature, while [10] pioneered empirical investigations into the determinants of the LCF. For a better understanding of the differences between the EKC and LCC hypotheses, both curves illustrating hypotheses are presented in Fig. 1.

In panel (a), the EKC hypothesis implies that once GDP per capita exceeds a certain level, a country acquires the ability to reduce pollutants (i.e., CO_2 emissions, EF). The LCC hypothesis in panel (b) shows that from the turning point onward, reducing the EF and increasing biocapacity can be achieved simultaneously with increasing income growth. The LCC differs from the EKC in that it considers environmental pressure and quality simultaneously.

The validity of both the EKC and LCC hypotheses is important for Germany. If either of these hypotheses is valid, the EG can automatically act as an instrument to enhance environmental quality. In addition, RD expenditures can have an indirect effect on environmental conditions by influencing energy consumption and EG [89]. Through innovative technologies, RD expenditures can increase production efficiency, reduce the consumption of natural resources and energy, and in this way indirectly reduce emissions and waste [90]. The technological progress driven by RD can effectively contribute to CO_2 minimization by improving the economic development model, strengthening the industrial structure, and adjusting the energy structure in an environmentally friendly way [91]. Therefore, RRD and NRD are also likely to contribute to the improvement of environmental quality. Fig. 2 shows the theoretical expectations for the effects of RRD, NRD, and EG on the environment.

NRD and RRD include expenditures on non-carbon environmental energy sources. Therefore, they are expected to have a negative sign in terms of reductions in CO_2 emissions and EF. For models in which CO_2 and EF are dependent variables under the EKC hypothesis, an inverted U-shaped relationship is expected between income and environmental pollutants in Germany. The LCF is an indicator of environmental quality, and NRD and RRD are expected to have a positive sign and a U-shaped relationship between EG and LCF.

4. Data, MODEL, and empirical methods

4.1. Data and model

The study utilizes annual data from 1974 to 2018. Also, the logarithmic form of the variables is used in the study to obtain the elasticity coefficient. Table 2 presents the measurements and data sources of the variables used in the study.

In the study, only GDP is used as a control variable, as the FADL method allows for the inclusion of up to four independent variables. The study tests the environmental effects of RRD and NRD by estimating Eqs. (1) to (3) under the EKC and LCC hypotheses.

$$lnCO_{2_t} = \tau_0 + \tau_1 lnGDP_t + \tau_2 lnGDP_t^2 + \tau_3 lnRRD_t + \tau_4 lnNRD_t + u_{1t} \tag{1}$$

$$lnEF_t = \mu_0 + \mu_1 lnGDP_t + \mu_2 lnGDP_t^2 + \mu_3 lnRRD_t + \mu_4 lnNRD_t + u_{2t} \tag{2}$$

$$lnLCF_t = \lambda_0 + \lambda_1 lnGDP_t + \lambda_2 lnGDP_t^2 + \lambda_3 lnRRD_t + \lambda_4 lnNRD_t + u_{3t} \tag{3}$$

where ln is the logarithm, τ_0, μ_0 and λ_0 are the intercepts,$\tau_{1\ to\ 4}$,$\mu_{1\ to\ 4}$, and $\lambda_{1\ to\ 4}$ are long-run coefficients, and $u_{1\ to\ 3}$ are error terms. For the EKC hypothesis to be valid, $\tau_1(\mu_1)$ must be positive, $\tau_2(\mu_2)$ must be negative, and both coefficients must be statistically significant. For the LCC hypothesis to be valid, λ_1 must be negative, λ_2 must be positive, and

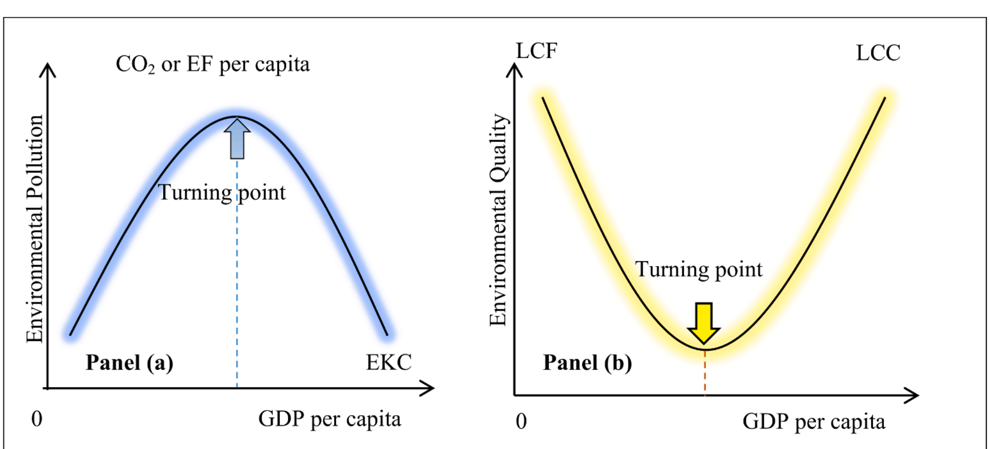

Fig. 1. The EKC and LCC Hypotheses .
Source: [12,13,15]

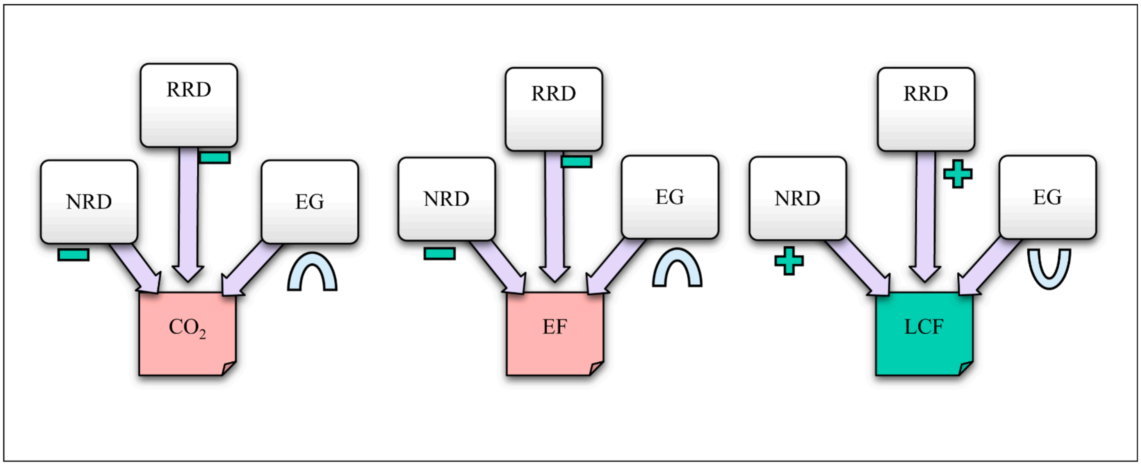

Fig. 2. Theoretical Expectations for the Signs of the Variables.

Table 2
The Details of the Variables.

Variable	Symbol	Unit	Source
Carbon dioxide emissions*	CO_2	Per capita, tons	[92]
Ecological footprint*	EF	Per capita, gha	[26]
Load capacity factor*	LCF	Biocapacity/EF	[26]
Gross domestic product	GDP	Per capita, Constant 2015 US$	[19]
Renewable energy research and development budgets	RRD	Public Budgets, Constant 2021 US$	[25]
Nuclear energy research and development budgets	NRD	Public Budgets, Constant 2021 US$	[25]

* *denotes the dependent variables.*

both coefficients must be statistically significant. In the EKC and LCC hypotheses, the technique effect is a step that means pollution can be reduced through environmentally friendly innovations. At this stage, innovation and technological development brought about by RD expenditures are important for enhancing environmental quality by minimizing biodiversity loss, offsetting temperature rise, and preventing flooding [93]. [94] suggests modifying the EKC equation to include RD expenditures because RD investments can play a key role in environmental improvements as income increases. According to endogenous growth theories, better technological adaptation associated with RD expenditures can yield environmental benefits [95]. Thus, following [72,90,93,96], this study modifies the EKC and LCC models with RD expenditures.

4.2. *Empirical methods*

After data collection and model specification, the study follows the empirical strategy shown in Fig. 3.

This study employs the Zivot and Andrews (ZA) unit root test with a structural break [97]. The ZA method is simply based on extending the Augmented Dickey & Fuller [98] test by using a structural shift and testing the "null hypothesis of the unit root" against the "alternative of stationarity" hypothesis. The empirical strategy of the ZA method with a break in the constant model (Eq. (4)) and a break in the constant and trend model (Eq. (5)) can be explained as follows:

$$y_t = \alpha + dD(T_B)_t + y_{t-1} + e_t \quad (4)$$

$$y_t = \alpha_1 + dD(T_B)_t + y_{t-1} + (\alpha_2 - \alpha_1)DU_t + e_t \quad (5)$$

where $D(T_B)_t = 1$ and $t = T_B + 1, 0$ otherwise;$DU_t = 1$ and $t > T_B, 0$ otherwise;$A(L)e_t = B(L)\upsilon_t, \upsilon_t \equiv iid(0, \sigma^2)$, and *A(L)* and *B(L)* are *pth* and *qth* order polynomials in the lag operator. To account for structural changes, Eqs. (4) and (5) can be further expanded as in Eqs. (6) and (7), respectively:

$$y_t = \alpha + \theta DU_t + \beta_t + dD(T_B)_t + \rho y_{t-1} + \sum_{i=1}^{k} \varphi \Delta y_{t-j} + e_t \quad (6)$$

$$y_t = \alpha_1 + \theta DU_t + \beta_t + dD(T_B)_t + \tau DT_t^* + \rho y_{t-1} + \sum_{j=1}^{k} \varphi \Delta y_{t-j} + e_t \quad (7)$$

To reveal the long-run associations among the series, this study performs the fractional frequency FADL method proposed by [99]. Unlike conventional cointegration estimators, ADL-type tests have more powerful size and power properties [100]. The FADL method allows researchers to consider possible structural shifts in the series with Fourier functions. Thus, there is no need to exogenously determine the breaks. Therefore, employing Fourier functions allows researchers to

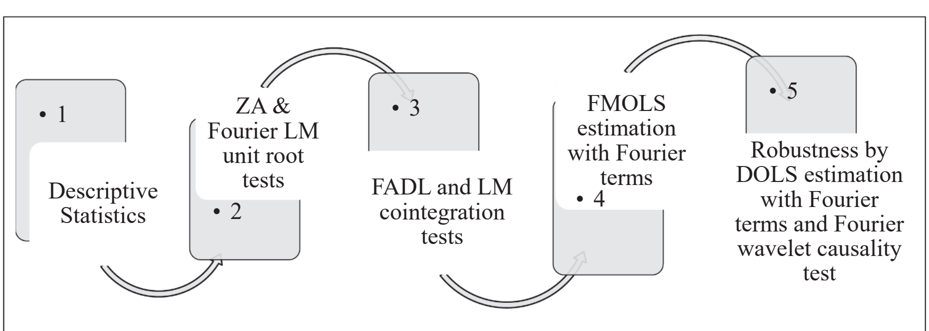

Fig. 3. Empirical Strategy.

deal with unknown structural changes and can help to obtain consistent results. Due to the coverage of smooth changes and the strong size and power characteristics, the FADL method is a suitable approach to analyze the environmental effects of RRD and NRD compared to traditional cointegration tests. To investigate cointegration using the FADL test, it is a prerequisite for all series to be I(1) [99]. The testing procedure of the FADL method can be explained in Eq. (8):

$$\Delta y_t = d(t) + \delta_1 y_{t-1} + \gamma' X_{t-1} + \varphi' \Delta X_t + \varepsilon_t \tag{8}$$

where γ, φ and X denote nx1 vectors of parameters and a set of regressors, respectively. $d(t)$ shows a deterministic term, y_t denotes the dependent variable, and δ_1 shows a scalar. Lags of Δy_t and ΔX_t are permitted to prevent serial correlation in residuals. [99] extended Eq. (8) by including Fourier functions to consider possible structural changes as in Eqs. (9) and (10):

$$\Delta y_t = \alpha_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \delta_1 (y_{t-1} + \beta' X_{t-1}) + \varphi' \Delta X_t + \varepsilon_{2t} \tag{9}$$

$$\Delta X_t = \psi' \Delta X_{t-1} + \varepsilon_{3t} \tag{10}$$

where y_{1t} and X_t are scalar and n-vector of I(1), respectively; and α_0 denotes the deterministic component of the estimation strategy including$(1,t)'$; $\varepsilon_{2t} \sim N(0,1)$, and $\varepsilon_{3t} \sim N(0,1)$, respectively. The FADL method adopts the null hypothesis of no cointegration$(H_0 : \delta_1 = 0)$. [99] conducted a t-test method to test whether$\delta_1 = 0$, and one can estimate the test statistic as in Eq. (11):

$$t^F_{ADL} = \frac{\widehat{\delta_1}}{se(\widehat{\delta_1})} \tag{11}$$

where $\widehat{\delta_1}$ denotes the OLS estimator of δ_1 in Eq. (8) while $se(\widehat{\delta_1})$ shows the standard error of $\widehat{\delta_1}$ obtained through Eq. (8). Besides, [101] emphasize that integer frequencies such as $k = 1, 2, ..., 5$, which imply temporary structural shifts, while fractional frequencies such as $k = 0.1, 0.2, ..., n$ allow researchers to model permanent structural changes in the estimations. Therefore, fractional frequencies are considered in the study when applying the FADL method. The study performs the elasticity calculations by incorporating Fourier terms in DOLS and FMOLS estimators, and in the final stage, the robustness of the results is checked with the Fourier wavelet causality test.

5. Empirical results

5.1. Descriptive statistics

The study first reviews the descriptive statistics for the empirical analysis and presents them in Table 3.

In Table 3, NRD and RRD have the highest volatility. The high volatility of energy RD budgets compared to other series indicates that RD data deviate more from the average than other series. While GDP has the highest mean and median values, the LCF has the lowest values. The mean and median values of the EF and CO_2 are lower than the energy-related RD activities.

Table 3
Descriptive Statistics.

Variable	lnCO_2	lnEF	lnLCF	lnGDP	lnRRD	lnNRD
Mean	2.456	1.780	−1.265	10.339	4.905	6.160
Median	2.448	1.770	−1.247	10.366	4.970	5.688
Maximum	2.656	2.006	−1.039	10.668	5.852	7.931
Minimum	2.205	1.541	−1.567	9.905	0.696	4.865
Standard Deviation	0.127	0.124	0.159	0.222	0.864	0.885

5.2. Unit root tests

After checking the statistical data of the variables, the unit root test is performed in the second step. Table 4 presents the results of the ZA unit root test, which is used to analyze the stochastic properties of the variables.

The structural break of the RRD in the ZA unit root test occurred in 2008. As Ahmed et al. (2021) stated, the situation that the development of renewables in the US is negatively affected by the 2008 financial crisis also applies to Germany. As for stationarity, the ZA unit root test indicates that all series contains a unit root at the levels and are stationary after the formation of the first differences. To check the robustness of ZA results, the study also uses the Fourier LM unit root test proposed by [102] and the outcomes are shown in Table 5.

The Fourier LM test statistics for all series with the values of the first difference are greater in absolute value than the critical values, and therefore, all series are found to be I(1). In other words, the findings of the Fourier LM test also show that all series are stationary in the first difference, as in the ZA test, so the cointegration relations between these series can be investigated by the FADL method.

5.3. Cointegration tests

Table 6 presents the outcomes of the FADL test.

The test statistics for the models, in which CO_2 and EF are dependent variables, exceed the critical values, confirming the existence of the cointegration relationship between the series. However, there is no cointegration between explanatory variables and the LCF because the $t^F_{ADL}(\widehat{k})$ test statistic is below the critical values in absolute values.

The study also tests whether cointegration changes after an endogenous structural break using the LM cointegration test of [104]. The LM cointegration test has strong power and small size bias, allowing the breakpoint to be determined with the best power [104]. The LM cointegration test uses two test statistics, t_S andΦ_S, for the regime shift model, and the findings of this approach are presented in Table 7.

The results of the LM cointegration test show that cointegration exists for two models, of which the dependent variables are lnCO_2 and lnEF, whereas there is no long-run association for the remaining model, of which the dependent variable is lnLCF. Thus, LM cointegration test results have expressed the reliability of the FADL cointegration findings.

5.4. Estimation results

In the next step, the long-run coefficients of the variables only for CO_2 and EF are estimated because the LCF does not have a cointegration. Table 8 shows the results of the estimates of the long-run elasticities based on the FADL models with the FMOLS approach including Fourier approximations.

The GDP coefficients are positive, the coefficients of GDP square are negative, and both these coefficients are statistically significant for the CO_2 and EF models. These results confirm the validity of the EKC hypothesis for Germany. Also, RRD expenditures appear to reduce CO_2 emissions. A 1 % increase in the RRD reduces CO_2 emissions by 0.03 %. However, the results confirm that NRD expenditures do not affect the environment.

Table 4
ZA Unit Root Test Results.

Variable	Level	Optimal Lag	Time Break	First Difference	Optimal Lag	Time Break
lnCO_2	−4.223	0	1984	−5.309**	4	1991
lnEF	−3.911	0	1981	−8.837*	0	1981
lnLCF	−4.342	0	2010	−6.906*	1	2002
lnGDP	−3.981	2	1988	−6.856*	1	1993
lnRRD	−4.436	3	2008	−10.239*	0	1983
lnNRD	−3.314	1	1986	−11.020*	0	1983

** and ** show the significance at 1 % and 5 % levels.*

Table 5
The Fourier LM Results.

Variable	Level	lag	frequency	First difference	lag	frequency
$lnCO_2$	−1.315 [−3.92] (−4.81)	5	2	−3.927** [−3.92] (−4.81)	5	2
lnEF	−2.666 [−3.92] (−4.81)	5	2	−5.326* [−3.45] (−4.26)	2	4
lnLCF	−1.421 [−3.50] (−4.37)	2	3	−6.885* [−3.50] (−4.37)	1	3
lnGDP	−3.085 [−3.92] (−4.81)	1	2	−6.244* [−4.79] (−5.54)	1	1
lnRRD	−1.296 [−3.46] (−4.24)	5	5	−6.692* [−4.79] (−5.54)	0	1
lnNRD	−3.655 [−4.79] (−5.54)	0	1	−9.950* [−4.79] (−5.54)	0	1

[ ] denotes 5 %, and () shows 1 % critical values derived from [103].

Table 6
Fractional Frequency FADL Cointegration Results.

Model	$t^F_{ADL}(\hat{k})$	$\hat{k}$	Lags	AIC
$lnCO_2 = f$(lnGDP, $lnGDP^2$, lnRRD, lnNRD)	−6.270*	1.00	ADL (1,1,2,1)	−4.996
lnEF = f(lnGDP, $lnGDP^2$, lnRRD, lnNRD)	−5.419**	1.30	ADL (1,2,1,2)	−4.536
lnLCF = f(lnGDP, $lnGDP^2$, lnRRD, lnNRD)	−3.723	0.10	ADL (1,2,1,1)	−3.595
Critical values	k = 0.10		k = 1.00	k = 1.30
1 %	−5.17		−5.83	−5.80
5 %	−4.51		−4.69	−5.26

** and ** show the significance at 1 % and 5 % levels. k = frequency.*

Table 7
LM Cointegration Test Results.

Model	t_S	Φ_S	Time break
$lnCO_2 = f$(lnGDP, $lnGDP^2$, lnRRD, lnNRD)	−4.352*	−51.037*	2002
lnEF = f(lnGDP, $lnGDP^2$, lnRRD, lnNRD)	−5.946*	−44.021*	2012
lnLCF = f(lnGDP, $lnGDP^2$, lnRRD, lnNRD)	−1.642	−3.879	2011
Critical values	t_S		Φ_S
10 %	−2.75		−15.0

** denote the significance at 1 % level.*

Table 8
FADL Long-Run Estimation Results with FMOLS Approach.

Model	CO_2		EF	
Variables	coefficient	p-value	coefficient	p-value
lnGDP	42.106*	0.000	43.888*	0.000
$lnGDP^2$	−2.056*	0.000	−2.141*	0.000
lnRRD	−0.039**	0.029	−0.014	0.484
lnNRD	0.021	0.427	0.038	0.280
SIN	0.027*	0.000	0.068*	0.000
COS	0.077**	0.015	0.030*	0.001
Constant	−212.882*	0.004	−223.162*	0.005
Turning point	US$ 27,888		US$ 28,186	

** and ** show the significance at 1 % and 5 % levels.*

5.5. Robustness

The study firstly applies the DOLS estimator including Fourier approximations for robustness check and the results are summarized in Table 9.

According to Table 9, the EKC hypothesis is valid for both EF and CO_2 in Germany. RRD is effective in minimizing environmental degradation, while NRD has no significant effect on CO_2 and EF. Thus, the DOLS results confirm the outcomes of FMOLS. Additionally, the study performs the Fourier Toda-Yamamoto causality test [105] by modifying it to include wavelet transforms. In this way, it provides a comprehensive causality analysis and meaningful results by taking into account the time and frequency dimensions of the variables as well as smooth changes [106]. To this end, the variables are first decomposed into short, medium, and long-run components. For this purpose, the study uses the Daubechies Least Asymmetric Scaling approach following [107] and chooses LA8 as the wavelet length. Finally, following [108], the study divides short-run (d1 + d2 = 2–8 years), medium-run (d3 = 8–32 years), and long-run (d4 + d5=+32 years) components. Then, the causality relations for the raw data and wavelet decomposed series are examined using the Fourier Toda-Yamamoto causality approach and the results are summarized in Table 10.

There is bidirectional causality in the medium and long-run between GDP and CO_2, and unidirectional causality in the medium and long-run from the EF to GDP. RRD and CO_2 emissions have bidirectional causality in the short, medium, and long term. In the medium and long-run, there is unidirectional causality from RRD to the EF. However, NRD does not affect the EF and CO_2 in any run. In the short term, there is only a causal relationship between RRD and CO_2. Other environmental effects of RRD and GDP are in medium and long-run. The fact that NRD is environmentally ineffective, while RRD and GDP affect environmental pollution makes the results of FMOLS and DOLS robust.

After the above-presented empirical examinations, Fig. 4 summarizes overall empirical long-run results.

As Fig. 4 presents, the EKC hypothesis is valid for both CO_2 and EF. However, the LCC hypothesis is not validated. This shows that Germany can achieve its carbon neutrality goals with an increase in income and a fight against environmental degradation. However, the invalid LCC hypothesis implies that Germany can still use its income more effectively to improve the supply side of nature. In addition, while RRD can reduce CO_2 emissions, it is not effective in reducing water, land, and soil pollution. The German policymakers need to increase the scope and amount of RRD expenditures and establish a more comprehensive investment plan for renewable energy technologies. The fact that NRD does not affect the environment is due to the German policymakers' selection of abolishing nuclear energy. These results underscore the need for German policymakers to effectively use renewable energy technologies and increase income in the fight against environmental challenges.

5.6. Discussion

In the study, it is defined that the GDP coefficients are positive, the coefficients of GDP square are negative, and both these coefficients are statistically significant for the CO_2 and EF models. These empirical results confirm the validity of the EKC hypothesis for Germany. According to [31], income is an important determinant of CO_2 in Germany. The

Table 9
FADL Long-Run Estimation Results with DOLS Approach.

Model	CO_2		EF	
Variable	coefficient	p-value	coefficient	p-value
lnGDP	57.802*	0.0007	18.337*	0.001
$lnGDP^2$	−2.814*	0.0007	−0.925*	0.001
lnRRD	−0.073**	0.0137	0.057**	0.0036
lnNRD	−0.025	0.7105	−0.067	0.1916
SIN	0.063*	0.0008	0.050**	0.037
COS	0.147**	0.0357	0.009	0.410
Constant	−293.615*	0.007	−88.702*	0.003
Turning point	US$ 28,755		US$ 19,988	

** denote the significance at 1 % level.*

Table 10
Causality Test Results with Fourier and Wavelet Transforms.

Null Hypothesis	Original Data	Decomposed Data		
		Short-Run	Medium-Run	Long-Run
$lnGDP \nrightarrow lnCO_2$	5.284 [0.110]	2.163 [0.180]	32.062 [0.000]*	20.869 [0.000]*
$lnGDP \nrightarrow lnEF$	1.333 [0.230]	0.638 [0.350]	28.135 [0.000]*	54.745 [0.000]*
$lnRRD \nrightarrow lnCO_2$	4.168 [0.120]	5.489 [0.030]**	14.886 [0.010]*	14.335 [0.030]**
$lnRRD \nrightarrow lnEF$	1.749 [0.201]	2.244 [0.141]	12.640 [0.010]*	6.242 [0.041]**
$lnNRD \nrightarrow lnCO_2$	0.408 [0.530]	0.020 [0.889]	0.467 [0.499]	0.869 [0.363]
$lnNRD \nrightarrow lnEF$	0.277 [0.617]	0.031 [0.859]	0.037 [0.867]	2.277 [0.580]
$lnCO_2 \nrightarrow lnGDP$	6.278 [0.040]**	1.377 [0.250]	29.040 [0.000]*	19.053 [0.000]*
$lnEF \nrightarrow lnGDP$	1.816 [0.150]	0.412 [0.560]	0.512 [0.780]	1.732 [0.450]
$lnCO_2 \nrightarrow lnRRD$	2.280 [0.190]	4.037 [0.050]**	1.916 [0.360]	12.077 [0.000]*
$lnEF \nrightarrow lnRRD$	0.706 [0.399]	1.954 [0.156]	5.619 [0.171]	0.304 [0.866]
$lnCO_2 \nrightarrow lnNRD$	0.664 [0.414]	0.378 [0.548]	2.108 [0.568]	8.204 [0.006]*
$lnEF \nrightarrow lnNRD$	0.253 [0.605]	0.014 [0.919]	0.904 [0.353]	0.671 [0.440]

[ ] shows bootstrapped probability values.

existence of EKC for Germany supports the findings of [109–110], which contradict the results of [111–112]. This implies that Germany can grow in a sustainable and eco-friendly way. Thanks to the composition and technique effect, the EG of Germany can provide financial resources that support the development of environmentally friendly energy technologies. In addition, rising income levels of citizens can increase demand for more environmentally friendly goods and services. Also, these circumstances can suppress German's demand for a greener environment and cleaner air, and a reduction in CO_2 emissions in turn. Hence, German policymakers can increase investments in renewable resources, such as wind and solar energy, especially as income rises.

Also, RRD expenditures have a curbing effect on CO_2 emissions. Differing from the studies of [30,70–71], these results are consistent with those, which are [35,74,113–114], suggesting that RRD improves environmental quality. As part of its Energiewende plan, which has been in place for 10 years, Germany is focusing on renewable energy sources and phasing out coal by 2038 to create a more efficient and low-carbon energy system [115]. In 2021, Germany invested $47 billion in the green energy transition to meet 41.1 % of its energy needs in the power sector, 16.5 % in the heat sector, and 6.8 % in the transport sector from renewable sources [116]. Reforms to the Renewable Energy Sources Act (EEG) in 2014–2017 have enabled Germany to rapidly reduce the cost of deploying wind and solar energy by making it easier to finance renewables [115]. Germany covers 18 % of its primary energy and 41 % of its electricity generation from renewable sources [117]. Germany is the only country in Europe that mandates the installation of solar panels on buildings at the national level and plans to switch to 100 % renewable power by 2040 [118]. All such incentives are important for Germany's renewable energy technologies to achieve its low-carbon goals. However, no statistically significant effect of the RRD on the EF is found. This is an indication that while sufficiently reducing air pollution, Germany's RRD has not yet been effective in reducing the EF. At the 47th G7 Summit, the German policymakers announced that it would increase climate finance from public budgets from four to six billion euros by 2025 [119]. The German policymakers can use part of this increase to develop RRD budgets more broadly and effectively to reduce the EF.

Moreover, the results confirm that NRD expenditures do not affect the environment. In contrast to [35,37], this finding supports the results of [70]. Although Germany considered and supported nuclear power as a bridging technology for low-carbon goals in 2009, it decided to completely phase out nuclear power by 2022 after the Fukushima Daiichi accident in 2011 occurred in Japan. With the thirteenth amendment to the Atomic Energy Act, German policymakers revoked the licenses for many nuclear power plants [115]. Germany's lack of support for nuclear power and its decreasing consumption confirms that NRD does not affect environmental quality. With the energy shortage caused by the Russia-Ukraine crisis, will Germany put its investment in nuclear energy technologies back on the agenda? This question is still under discussion today and it will be interesting to see what the German authorities will do in the future. However, in researchers' opinion it is not likely to go back to using nuclear power plants in the long-run, but using them can be considered as a temporary choice under the current energy crisis in Europe.

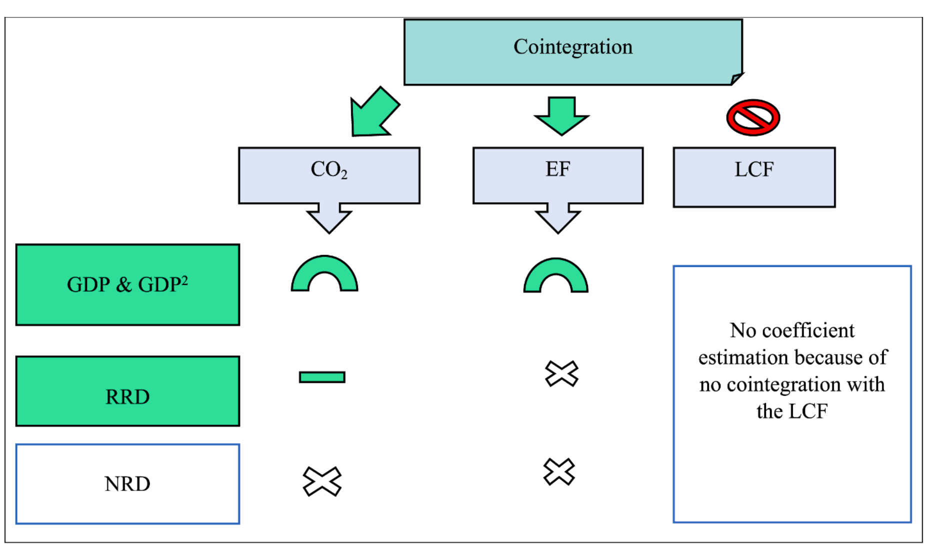

Fig. 4. Summary of the Empirical Results.

6. Conclusion and policy inferences

As one of the largest economy and bigger CO_2 emitting countries in Europe, Germany's measures regarding the environment and climate protection are important for both ensuring sustainability of German economic activities and the global economy. In this context, Germany has targeted to have a carbon–neutral economic structure by 2045. Accordingly, Germany has set out an ambitious roadmap to vastly increase its renewable energy supply, reduce its dependence on external sources for energy, and increase the use of environmentally friendly technologies by 2030. Naturally, the success of such an ambitious plan depends to a significant extent on the state of knowledge and technology related to environment-friendly energy sources. To understand the effect of investments in knowledge and research efforts in energy-related technologies, this study examines the effect of renewable and nuclear energy RD expenditures on environmental quality and tests the validity of the EKC and LCC hypotheses for Germany.

The estimation results demonstrate that the EKC hypothesis is valid for Germany, whereas the LCC hypothesis is invalid. Also, the long-run estimation results confirm that RRD expenditures can be an effective policy tool in reducing CO_2 emissions. However, NRD expenditures are not statistically significant in the environment. Because there is no previous study examining the environmental effects of RRD & NRD considering smooth structural changes, the results of this study are novel and critical for both Germany as well as other countries' policymaking processes. Also, the EKC threshold income level is estimated at around $28,000 per capita. Considering that Germany is already above this income level, German policymakers can prevent the scale effect of the EKC hypothesis by limiting resource use and promoting the composition and technique effect of the EKC hypothesis by enhancing productivity, knowledge, and technology levels.

The composition effect is closely related to the conversion of production patterns, such as the reduction of resource consumption and energy intensity of economic activities, while the technique effect is closely related to the increasing level of knowledge and technology. In this respect, German policymakers can focus on transforming the energy mix used in the economy. To this end, an increasing share of renewable sources in the energy mix can be evaluated as the most efficient way to limit the use of non-renewable resources. In other words, reducing the share of non-renewable energy for each pair of GDP can accelerate the composition effect of the EKC hypothesis. German policymakers can focus on raising renewable energy production capacity to change the energy mix permanently. Therefore, renewable energy investments in Germany have key importance. Although Germany has an enforceable plan, such as the "Green Budget", to stimulate investments in renewable energy, it allocates fewer resources to renewable energy investments relative to its GDP compared to the world's largest economies, such as the US, China, and Japan. For example, Germany spent about 0.14 % of its GDP on renewable energy investments in 2019, whereas China, Japan, and the US allocated nearly 0.62 %, 0.34 %, and 0.28 % of their GDP, respectively [120]. To transform Germany's energy mix by also protecting the competitiveness of its economy and businesses, German policymakers can consider anchoring renewable energy investments with the average investment levels of prominent renewable energy investing countries.

To strengthen the technique effect of the EKC hypothesis, increasing the level of knowledge and technology is another significant task for German policymakers. To increase technological capacity, policymakers can pay attention to the funding and composition of RD activities. To this end, Germany can provide more funding sources for RD programs. Increasing RD budgets can facilitate the efforts of RD in Germany, which in turn would boost the productivity of any resource invested in this area. To create an efficient mechanism for maintaining and increasing the competitiveness of RD institutions, German policymakers can consider aligning RD budgets for green technologies with the average RD budgets of prominent countries. In this way, increasing funding sources for RD can help enhance the productivity of German companies, which in turn will help achieve the required capacity for ambitious plans, such as the Green Budget and the carbon–neutral economy until 2045.

Another important task for German policymakers is to determine how to allocate budgetary resources for RD activities. The empirical research shows that RRD expenditures can reduce the environmental burden of economic development, whereas there is no trade-off between NRD budgets and environmental quality. Although [121] emphasizes that the main source of energy transition and electricity generation is renewable energy, non-renewable energy sources still account for a large share of the total energy mix in Germany as of 2021 [122]. It can be concluded that Germany has a lot to do with the technological transformation of production. In this context, RD expenditures on renewable energy become essential tools from an environment perspective. German policymakers can consider increasing the share of RRD expenditure in total RD expenditures to reduce the share of non-renewable energy in total energy consumption, improve the competitiveness of German companies, and clear up existing doubts about the performance of German private companies in the field of renewable energy [123]. Increasing the credibility of green transformation programs and reducing foreign dependence on fossil resources, such as natural gas, are also important options. Allocating more funding to RRD expenditures than to other low-carbon energy technologies can help the German economy move toward a carbon–neutral economic pathway. Also, more investment in renewable energy can promote both EG and ecological quality.

Although this study focuses on the role of RD expenditures in renewable and nuclear energy by also exploring the validity of the EKC and LCC hypotheses for the German case, there are still some deficiencies. Since the study handles only the German case, it does not include other major economies. Therefore, new studies can examine other countries (e.g., the UK and France). Second, the data in this study ends in 2018 because three environmental quality indicators are included at the same time. As more updated data become accessible, new studies can be conducted to assess the most recent condition. Third, this study makes coefficient estimations. Hence, future studies can apply time or quantile-varying methods, such as wavelet transform coherence, rolling windows causality, and quantile-on-quantile regression, to provide new insights about how environmental effects of RRD and NRD change based on times, frequencies, and quantiles.

7. Declarations

Funding: none, not applicable.

Ethical approval: This article does not contain any studies with human participants performed by any of the authors].

Consent for publication: Our study does not contain a person's data.

Consent to Participate: No human or animal subjects were used in our study, and no questionnaire was conducted.

Data availability: The data will be made on reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

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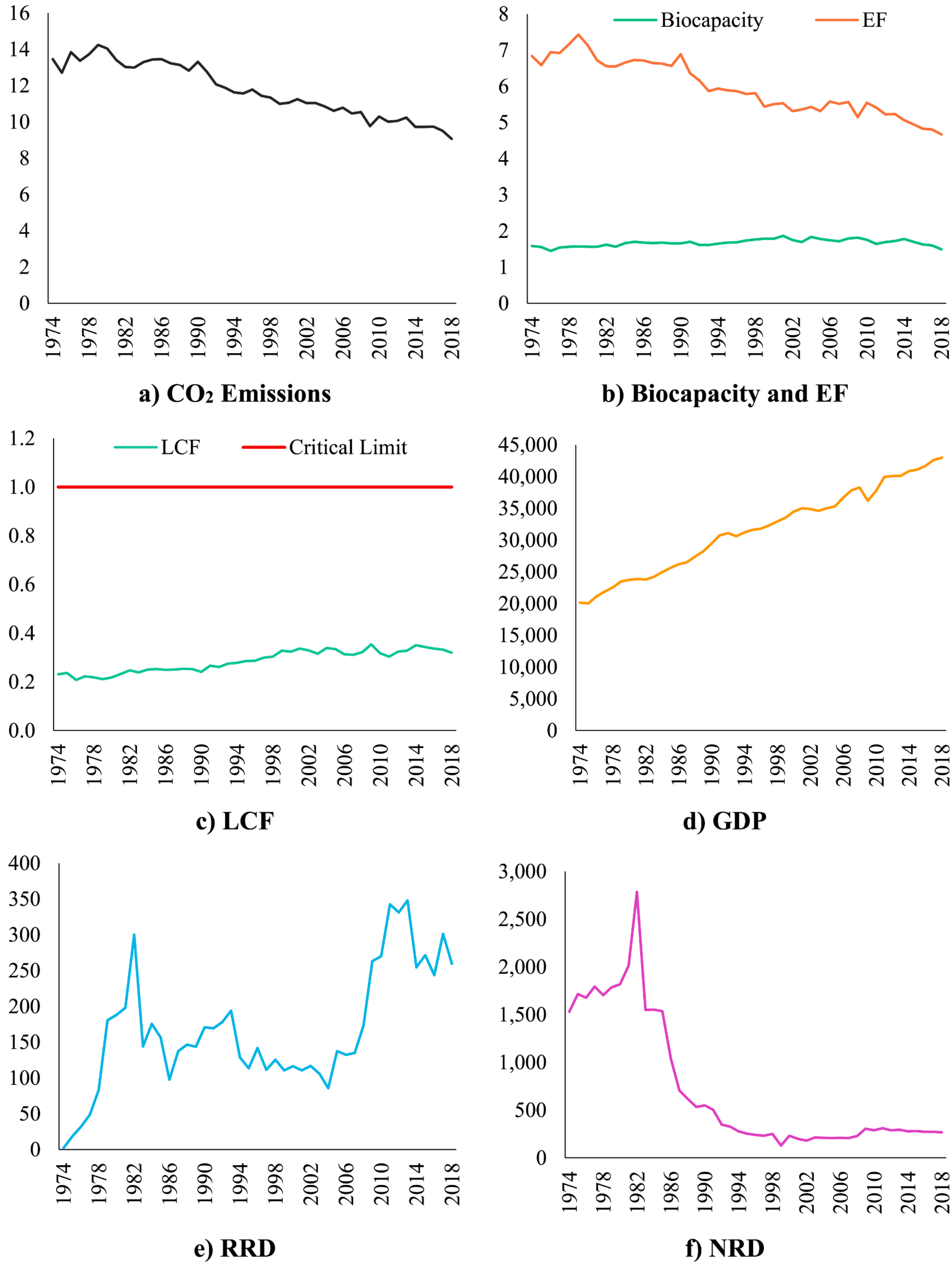
Appendix A. Time Paths of the Indicators



Unit for CO_2 emissions is per capita tons, unit for biocapacity and EF is per capita global hectares (gha), unit for GDP is per capita US$, and unit for RRD and NRD is one million US$.

Source: GFN (2022), IEA (2022), Our World in Data (2022), World Bank (2022).

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